AD-A069 160   OCEAN CITY RESEARCH CORP N J   F/G 11/3

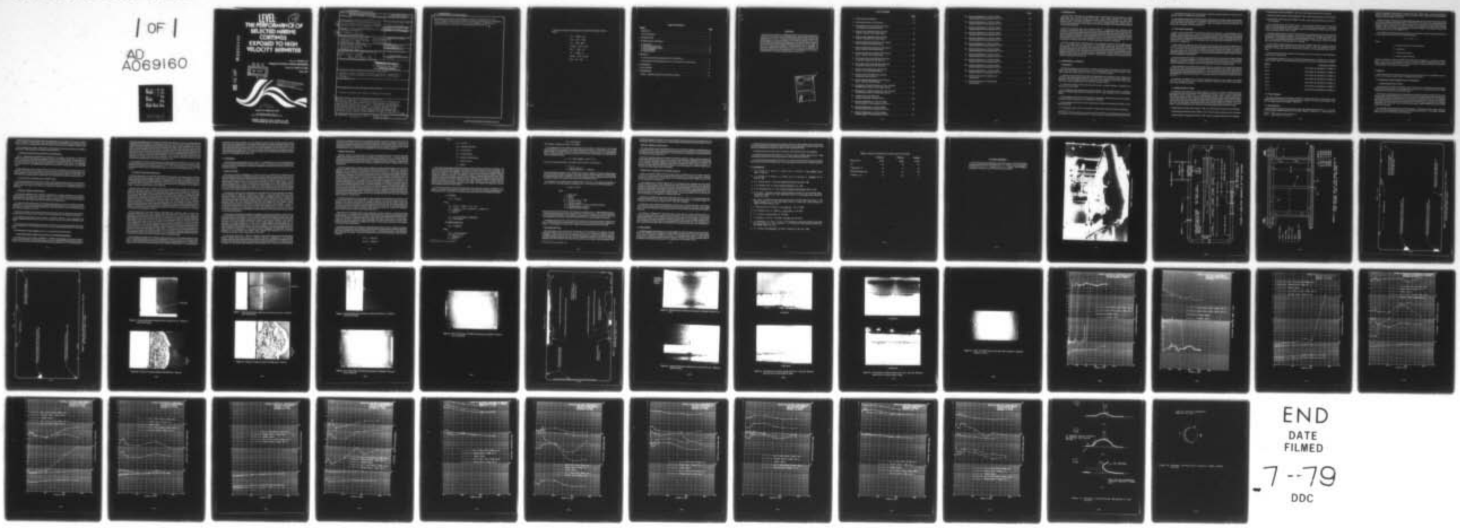
THE PERFORMANCE OF SELECTED MARINE COATINGS EXPOSED TO HIGH VEL--ETC(U)

MAR 79   G A GEHRING   N00014-77-C-0509

UNCLASSIFIED   NL

| OF |

AD
A069160



END
DATE
FILMED
7--79
DDC

THE PERFORMANCE OF SELECTED MARINE COATINGS EXPOSED TO HIGH VELOCITY SEAWATER

By G. A. GEHRING, JR.

Prepared for OFFICE of NAVAL RESEARCH

Contract No. N00014-77-C-0509

March 1979

OCEAN CITY RESEARCH CORP.

PSC PROFESSIONAL SERVICES GROUP, INC.
A Member of the Corporate Family of PHILADELPHIA SUBURBAN CORPORATION

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) The Performance of Selected Marine Coatings Exposed to High Velocity Seawater,		5. TYPE OF REPORT & PERIOD COVERED Final, 8/77 to 8/78
		~~6. PERFORMING ORG. REPORT NUMBER~~
7. AUTHOR(s) (10) G. A. Gehring, Jr		~~8. CONTRACT OR GRANT NUMBER(s)~~ (15) N00014-77-C-0509
9. PERFORMING ORGANIZATION NAME AND ADDRESS Ocean City Research Corporation Tennessee Ave. & Beach Thorofare Ocean City, NJ 08226		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (12) 52 p.
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Code 471 Metallurgy Program Office Arlington, VA 22217		12. REPORT DATE (11) March, 1979
		~~13. NUMBER OF PAGES~~
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (9) Final rept. Aug 77-Aug 78,		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; distribution unlimited. Reproduction in whole or in part is permitted for any purpose of the United States Government.

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Protective Coatings, High Velocity, Seawater, Flow Channel

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study was undertaken to investigate seawater velocity thresholds and failure modes for three selected marine coatings under non-cavitating, parallel flow ranging from 3 to 30 m/s. The study was accomplished in a flow channel using natural seawater. The results indicate: (1) the velocity threshold for two of the three coatings investigated might exceed 30 m/s (2) blister formation appears to be the critical part of the damage process leading to gross failure (3) under the given set of

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

409 286

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

experimental conditions, hydromechanical wear is negligible (4) electrical impedance measurements enable non-destructive detection of impending coating failure (5) parallel flow is not as damaging as impinging or cavitating flow in the velocity range between 15 and 30 m/s.

The metric units used in this report can be converted to English units as follows:

m/s ÷ .3048 = ft/s

m/s ÷ .514 = knots

l/s ÷ .063 = gpm

microns ÷ 25.4 = mils

mm^2 ÷ .645 = in^2

m^2 ÷ .0929 = ft^2

newton ÷ 4.45 = pound

Kpa ÷ 6.9 = psi

TABLE OF CONTENTS

ABSTRACT

A study was undertaken to investigate seawater velocity thresholds and failure modes for three selected marine coatings under non-cavitating, parallel flow ranging from 3 to 30 m/s. The study was accomplished in a flow channel using natural seawater. The results indicate: (1) the velocity threshold for two of the three coatings investigated might exceed 30 m/s; (2) blister formation appears to be the critical part of the damage process leading to gross failure; (3) under the given set of experimental conditions, hydromechanical wear is negligible; (4) electrical impedance measurements enable non-destructive detection of impending coating failure; (5) parallel flow is not as damaging as impinging or cavitating flow in the velocity range between 15 and 30 m/s.

LIST OF FIGURES

I. INTRODUCTION

In recent years, there has been considerable effort directed toward the development of higher speed ships (e.g. hydrofoil, surface effect ships). High velocity seawater can cause rapid deterioration of many structural materials. For many materials, the relative stability in high velocity seawater needs to be better documented. One class of materials deserving detailed study is anti-corrosive coatings that could be used to provide corrosion protection for structural alloys exposed to high velocity seawater.

Most of the pertinent high velocity coating studies[1-7] to-date have been conducted under cavitation or impingement-type flow. Under the flow conditions established in these previous studies, conventional marine coatings (sprayable, solvent-type coatings) failed quite rapidly (often within 1 to 10 hours). Elastomeric coatings, of types not widely used in the marine industry, generally exhibited better performance. However, many of these better performing, elastomeric coatings involve rather sophisticated application techniques compared to the more conventional marine coatings. Some of the elastomeric coatings might pose formidable application problems in shipyards.

While it is recognized that a high speed ship will be subjected to cavitation and impingement-type flow, it would seem that the major portion of its exposed surface will see simple, parallel, non-cavitating* flow. The conventional marine coatings might exhibit better stability at the higher velocities under parallel, non-cavitating flow conditions than under cavitating flow conditions. There appears to be dearth of data in the literature on the performance and stability of conventional marine coatings in high velocity, non-cavitating seawater. Consequently, this study undertook to investigate seawater velocity thresholds and failure modes for three marine coatings under non-cavitating flow conditions ranging from 3 to 30 m/s.

II. EXPERIMENTAL APPROACH

A. Background

The laboratory aparatus used primarily in previous velocity studies has included a rotating disk, water tunnel, waterwheel, and impinging jet. Each of these apparatus was disadvantageous for high velocity seawater coating studies for one or more of the following reasons:

1. The size of the test specimen imposed by the apparatus was unreasonably small resulting in an artificially high edge-to-surface area ratio. Coating failures often initiate at sharp edges where complete, uniform coverage is difficult to attain. Also, fully developed uniform flow is difficult to attain with small-size specimens and the attendant boundary effects.

2. The nature of the high velocity flow was often complex, not easily definable or relatable to the actual service environment.

3. The apparatus used recirculated synthetic seawater. This prevented long term exposures because of problems associated with temperature control, water stagnation and/or concentration effects.

4. The apparatus did not permit the development separately of different types of flow (cavitating, impinging, parallel) depending on the objectives of the study.

5. The apparatus was velocity-limited considering the present day anticipated velocities of high speed naval ships.

6. The apparatus was limited in the number of materials that could be studied simultaneously.

*It is realized that at sufficiently high velocities, small surface protrusions present either initially, or those that develop during actual service due to blistering or the like, can cause localized cavitation or be subject to impingement which might possibly lead to premature failure.

7. A comprehensive study over a broad velocity range was impractical because of high setup and teardown costs or untenable time requirements.

A flow channel available at the OCRC laboratory overcomes all of the above-listed disadvantages. The flow channel permits exposure of significantly larger test panels than heretofore possible with other high velocity test apparatus. Consequently, edge and boundary effects are minimized. The panels can be exposed to simple, parallel flow.

B. Flow Channel Description

Figure 1 pictures the OCRC flow channel as originally constructed. It accommodated natural seawater velocity studies up to $\simeq 18$ m/s. The width of the channel cross-section varies along the length to permit testing at 6 different flow velocities simultaneously. Later, the channel was modified to permit testing in a separate section at higher velocities. Figure 2 presents a simplified schematic of the channel as it currently exists. For the subject study, the nominal velocities were 30, 18, 15, 12, 9, 6 and 3 m/s, respectively.

Figure 3 shows the method by which test panels were mounted in the low velocity section (3 m/s thru 18 m/s) of the channel. Each velocity subsection accommodated 5 test panels (17.5 cm x 25.5 cm x $\simeq$ 1.3 cm thick). The test panels were spaced 5 cm apart using phenolic spacers to maintain a continuous center wall in each section. The interface between spacer and panel was matched as precisely as possible to avoid edge effects. Electrical leads were attached to each test panel to permit electrical impedance measurements.

In the high velocity section (30 m/s), the test panels were fitted into slots which had been precisely machined in the acrylic sidewalls. The test panels were carefully shimmed to minimize edge mismatch and eliminate cavitation. As in the low velocity section, provisions were made for external electrical connection to the panels to permit the acquisition of electrical impedance data.

Natural seawater is circulated through the channel by a double-suction centrifugal pump powered by a 100 H.P. motor. The flow rate can exceed 300 l/s and is measured using a factory-calibrated 316 SS orifice plate/differential pressure gauge set-up. The rate of seawater make-up into the channel is adjusted to control seawater temperature within $\pm$ 2.5°C while being maintained sufficiently high to avoid stagnation or concentration effects. For the subject studies, the make-up rate varied between 2 and 5 l/s.

The channel was designed to provide high Reynolds number, Re, flow at each test velocity ($Re \simeq 10^6$). This was done in order to better simulate flow conditions that might be encountered during high speed ship operation.

C. Coatings Selected For Study

In selecting three representative marine coatings for study, this author contacted cognizant personnel within the Navy as well as marine coating manufacturers. Personnel from the Naval Ship Engineering Center advised that a polyamide-epoxy coating system meeting specification MIL-P-24441 was widely used on Navy ship hulls. Representatives of Devoe and Raynolds Company, a major manufacturer of marine coatings, recommended a modified epoxy coating system as being best suited for marine hull applications. Personnel from the Naval Research Laboratory, with whom this work was coordinated, recommended that a coal tar-epoxy coating be included in the study. Based on these considerations, the following three coating systems were selected for study:

1. Polyamide Epoxy Primer (MIL-P-24441, F150) - 75 to 100 microns nominal dry film thickness

   Polyamide Epoxy Mid-Coat (MIL-P-24441, F151) - 50 to 75 microns nominal dry film thickness

   Polyamide Epoxy Topcoat (MIL-P-24441, F156) - 50 to 75 microns nominal dry film thickness

2. Polyamide Epoxy Primer (DEVRAN® 201) - 50 to 75 microns nominal dry film thickness

Modified Polyamide Epoxy Topcoat (DEVRAN® 230) - 200 microns nominal dry film thickness

3. Coal Tar-Epoxy, Polyamide Cured (TARSET® C-200) - 2 coats, each at 200 microns nominal dry film thickness

The first coating system, MIL-P-24441 Epoxy, is used throughout the Navy as an anti-corrosive coating on both surface ships and submarines. It is a two-part epoxy coating with $\simeq$ 56% solids volume. It is usually applied in 3 coats to obtain a total dry film thickness of $\simeq$ 200 microns ($\simeq$8 mils). It can be applied by brush, roller, or spray.

The second coating system consists of the DEVRAN 201 Polyamide Epoxy primer and DEVRAN 230 Modified Polyamide Epoxy topcoat. The 201 primer meets the MIL-P-24441 specification. The 230 topcoat is a hydrophobic hydrocarbon modified polyamide epoxy. The 230 topcoat has volume solids $\simeq$ 65% and is designed to achieve a dry film thickness of $\simeq$ 200 microns ($\simeq$8 mils) in a single coat. Spray application is recommended for the topcoat.

The third coating system selected for the study was TARSET C-200 Coal Tar-Epoxy. The two component system is polyamide cured and has a volume solids of $\simeq$76%. It is designed to achieve a high build in a single coat, normally $\simeq$200 microns ($\simeq$8 mils). It can be applied by brush, roller, or spray.

These three coating systems probably are representative of the anti-corrosive marine coatings in major use at the present time.

The coatings were applied by air spray to ASTM A-36 steel panels (17.5 cm x 25.5 cm x 1.3 cm) grit blasted to white metal. The test panel exposure sequence as a function of velocity was as follows:

Velocity	Coating (No. of Panels)
30 m/s	MIL-P-24441 (2), DEVRAN (1), TARSET (1)
18 m/s	MIL-P-24441 (2), DEVRAN (2), TARSET (1)
15 m/s	MIL-P-24441 (2), DEVRAN (2), TARSET (1)
12 m/s	MIL-P-24441 (2), DEVRAN (2), TARSET (1)
9 m/s	MIL-P-24441 (2), DEVRAN (2), TARSET (1)
6 m/s	MIL-P-24441 (2), DEVRAN (2), TARSET (1)
3 m/s	MIL-P-24441 (2), DEVRAN (2), TARSET (1)

D. Time of Exposure

The coated panels were simultaneously exposed to uninterrupted flow for 812 hours at each velocity from 3 m/s thru 18 m/s (low velocity section of channel). In the high velocity section, at 30 m/s, the coated panels were exposed for 898 hours.

E. Data Acquisition

Data acquisition during the study included weight loss measurements (sensitivity = ± 1 gram), dry film thickness measurements (prior to and after exposure – sensitivity = ± 25 microns), and

DEVRAN® - registered trademark of Devoe and Raynolds Co.
TARSET® - registered trademark of Porter Paint Co.

electrical impedance measurements. Seawater data was obtained daily including temperature, salinity, dissolved oxygen concentration, pH, and turbidity. Table I presents the average seawater chemistry over the course of the study.

Electrical impedance (resistance and capacitance) was measured in situ between the coated panels and platinum reference electrodes located in the sidewalls of the channel. The measurements were made at different times during each velocity exposure using a General Radio Type 1650 Impedance Bridge at 3,000 Hz. Changes in the electrical resistance and capacitance of high dielectric coatings exposed in low resistivity electrolytes generally correlate to changes in the protective nature of the coating as shown by many investigators [8-11].

An increase in electrical capacitance corresponds to a reduction in effective coating thickness due to water penetration as seen from the following equation:

$$K = 11.3\,C\,t \div A$$

where,

K = dielectric constant of the coated panel

C = capacitance

A = exposed surface area

t = effective coating thickness

Similarly, a decrease in electrical resistance signifies physical breakdown of the coating allowing water to short circuit the high dielectric barrier. Electrical impedance measurements are useful because often they allow early detection of significant changes in coating performance not obvious by visual inspection. Also, they are non-destructive.

III. RESULTS

Coated panels of each of the selected coating systems were exposed at 30 m/s for 898 hours and at 18, 15, 12, 9, 6 and 3 m/s for 812 hours. The results are as follows:

A. Performance of Panels Exposed at 30 m/s For 898 Hours

1. Polyamide-Epoxy (MIL-P-24441)

Two panels were exposed of this coating system. Figures 4 and 5 characterize the deterioration observed on the test panels as it developed throughout the test run. Figures 6 thru 10 are actual photographs of the observed coating deterioration.

The first sign of coating deterioration was observed on Panel #1 (upstream panel) at 181 hours into test (Figure 6). Coating disbonded over about a 2 cm^2 area on the leading edge. This coating holiday remained approximately the same size over the remainder of the exposure. Corrosion of the exposed steel substrate occurred quite rapidly and at the end of the exposure a pit of .300 mm was measured (Figure 6a). The apparent stability of the coating about the initial holiday was surprising. It had been anticipated that, in the event of such a failure at this velocity, coating disbondment would proceed rapidly from this point.

The next observed failure occurred on the same panel at $\simeq$ 349 hours into test. Again, the failure was in the form of disbondment intitiating at the leading edge (Figure 7). The holiday remained stable in size over the remainder of the test period.

Similar coating failure occurred on panel #2 (downstream panel) at 463 and 510 hours into test as shown in Figure 8. These holidays also were stable over the remainder of the exposure period. Figures 9 and 10 are photographs of each test panel upon completion of the 898-hour exposure test.

Upon completion of the tests, small blisters were detected at random locations along the edges of both panels. These locations are identified in Figures 4 and 5.

2. Modified Polyamide Epoxy (DEVRAN 201/DEVRAN 230)

Figure 11 characterizes the deterioration observed on this coating over the test run. Figure 12 shows the test panel after 898 hours exposure. Failure of this coating system first occurred at 54 hours. The failure was in the form of disbondment along the bottom edge (Figure 13). The holiday did not remain stable over the test period, but continued to increase in size (Figure 14). Significant corrosion occurred on the exposed steel substrate. The maximum pit depth was .517 mm after 898 hours.

At about 460 hours into test, disbondment of the coating was observed on the upper edge of the test panel. This holiday also continued to increase in size over the rest of the test period (Figure 15). Final inspection of the test panel showed random blistering along the edges of the test panel. The DEVRAN coating system suffered significantly more damage than the other coatings at 30 m/s.

3. Coal Tar-Epoxy, Polyamide-Cured (TARSET C-200)

The one panel coated with coal tar-epoxy did not exhibit detectable deterioration over the 898 hour velocity test (Figure 16). Final inspection revealed slight blistering at a few isolated spots along the bottom edge. The coated panel showed no significant weight loss or measurable reduction in thickness.

4. Electrical Impedance Measurements

The electrical capacitance and resistance measurements correlated excellently with observed coating behavior over the course of the test. Figures 17 and 18 present the data. Sharp changes in capacitance and resistance were measured at about the same time initial coating failures were observed for the MIL-P-24441 epoxy and DEVRAN epoxy-coated panels.

For panel #1, MIL-P-24441 epoxy, the measured capacitance at 174 hours was 60.3 nanofarads whereas prior to this time the capacitance had been fairly stable between 6 to 11 nanofarads. At the same time, the measured resistance decreased from 8500 to 2750 ohms. Failure on this panel was first observed visually at 181 hours.

The other MIL-P-24441 epoxy coated panel showed a significant shift in capacitance and resistance between 397 and 463 hours in test. Failure on the coated panel was first observed at 463 hours.

The DEVRAN epoxy-coated panel exhibited a significant change in both capacitance and resistance between 39 and 54 hours into test. The first sign of failure on this panel was detected at 54 hours.

The capacitance and resistance data were fairly constant for the coal tar-epoxy coated panel over the entire test period. This corresponds favorably with the observed stable behavior of the coated panel.

B. Performance of Panels Exposed at 18, 15, 12, 9, 6 and 3 m/s For 812 Hours

1. Visual Observations, Weight Loss and Dry Film Thickness Measurements

Five coated panels (2 MIL-P-24441, 2 DEVRAN, 1 TARSET) were exposed for 812 hours at each of the above-listed velocities. Leading edge failure in the form of disbondment was observed within the first hour after start-up on the first panel (DEVRAN epoxy) exposed in the 15 m/s velocity section.

This panel was exposed without the benefit of a spacer plate ahead of it. Thus, the leading edge was subjected to both cavitation and impingement-type flow. The first panel exposed in the 18 m/s velocity section was preceded by a spacer place so that, essentially, it saw only parallel flow. The first panels in the other velocity sections were not preceded by a spacer plate, however, coating failure was not visually detectable over the duration of the test. Except for the above-noted panel and one other panel, none of the remaining 28 panels exhibited visually detectable coating damage over the 812 hour test period. The coating damage observed on the other panel represented a small chip in the coating at the bottom edge of the panel (DEVRAN at 3 m/s) that most likely occurred during installation or removal of the panel from the channel. Final inspection disclosed a slime film with some attendant algae growth on the panels exposed at 3 m/s.

Upon completion of the 812 hours exposure, the coated panels were allowed to air dry for 5 days, then weighed. Except for the panel which suffered leading edge failure, none of the remaining panels exhibited a measurable loss of weight (sensitivity = ± 1 gm). Correspondingly, dry film thickness measurements failed to show a measurable decrease in the coating film thickness (sensitivity = ± 25 microns.

2. Electrical Impedance Measurements

Electrical capacitance and resistance measurements were made on all coated panels at different times during the velocity exposure. Figures 19 thru 30 present the data. The capacitance values measured on each panel immediately after start-up ranged over four orders of magnitude, from a low of 16 nanofarads to a high of 42,280 nanofarads. The initial values of resistance varied from a low of 24 ohms to a high of 10,000 ohms. There was no observed trend for one coating to be consistently higher or lower compared to the other two coatings.

The wide range of the initial impedance values was unexpected. Great care had been exercised in preparing the coated panels to insure that each panel was initially exposed in a holiday-free condition. After coating application, all panels had been inspected with a wet-sponge, low-voltage (67.5 volts) holiday detector. All holidays that were detected were repaired. All edges had been double-coated. After following these precedures and before inserting the panels in the channel, capacitance and resistance measurements were made on each coated panel when immersed in mercury. The values of capacitance and resistance measured in mercury were all within the same order of magnitude. It is the opinion of the author that, with one exception, the wider range of capacitance and resistance values measured immediately after start-up reflects differences in the degree of damage that occurred inadvertently on coated panel edges and/or the electrical lead wire insulation during insertion and positioning of the panels in the channel. The positioning of the panels in the channel was necessarily a tight fit.

The one panel where the initial values of capacitance and resistance appear to have been significantly affected by flow was the leading panel (DEVRAN epoxy) in the 15 m/s section. As mentioned, this panel had not been preceded by a spacer plate and suffered visually detectable leading edge failure immediately after start-up. The initial value of capacitance (42,280 nanofarads) was higher by a factor of over ten than the other initial capacitance values. At the same time, the initial resistance was lower by better than a factor of ten. This data is significant in that it provides a relative gauge as to what values of capacitance and resistance correspond to gross failure that is visually detectable. In other words, changes in capacitance and resistance toward values approching those measured on the failed DEVRAN epoxy panel correspond to gross failure as opposed, for example, to a few minute pinholes not visually evident. It is noteworthy that throughout the entire test run only one other panel (DEVRAN epoxy at 3 m/s) exhibited impedance values approaching those measured initially on the failed panel at 15 m/s. As mentioned, the DEVRAN epoxy panel at 3 m/s was the only other panel which exhibited visually detectable damage.

The most significant aspect of the impedance data is that only 5 of the 30 exposed panels showed order of magnitude changes over the entire measurement period and except for the panel noted above, none exhibited values approaching the range that would suggest gross failure. The majority of coated panels exhibited fairly stable capacitance and resistance characteristics. This correlated with

the results of the final inspection. The only indication of failure were pinholes, primarily around edges, that were detected using a low-voltage holiday detector. Neither the impedance data nor the final inspection provided clear-cut evidence that one coating system was better than another or that there was a predominant velocity effect over the range investigated. For the most part, all of the coating systems were stable over the 812-hour test period. Also, extrapolation of apparent trends in the impedance data suggests that, for a majority of the panels, the coating systems might have been stable for a considerably longer test period.

IV. DISCUSSION

The subject study was somewhat narrow in scope — it investigated only 3 marine coatings applied to a steel substrate and exposed to parallel flow. However, the results do provide some basis for projecting velocity thresholds and considering probable failure modes under the high velocity flow conditions examined.

Velocity Thresholds

The maximum velocity investigated in the study was 30 m/s ($\simeq$60 knots). As reported, gross coating damage occurred on one (DEVRAN epoxy) of the four coated panels exposed at 30 m/s while the other 3 panels exhibited varying degrees of lesser damage occurring primarily near the edges. At the lower velocities (3 m/s thru 18 m/s), there was only one incidence of gross failure — on the leading edge of a panel exposed to impinging and cavitating flow. If one chose to ignore the area close to the edge (within $\simeq$ 1-2 cm), the test results would indicate that 3 of the 4 panels at 30 m/s suffered negligible coating damage over the 900 hour exposure period. It could then be inferred that two of the three coating systems were stable up to and including 30 m/s and that the velocity threshold of these coatings exceeds 30 m/s for the given set of flow conditions and exposure period.

In attempting to project velocity thresholds from the subject study, the critical question is whether failure originating at edges can legitimately be ignored or, along the same lines, how much importance should be attached to edge damage. Many investigators choose to minimize the importance of failure occurring at edges because of the difficulty in obtaining a uniform, holiday-free coating along the edge. The reasoning is that the edge to surface area ratio on a test panel is often atypically higher than most service applications and, since edges are more prone to failure, time-to-failure data might be misleading if edge failures are given equal weight. It would be unreasonable to assume that a ship hull will be free of sharp edges, burrs, or the like. However, in the opinion of the author, the relative edge to surface area ratio characteristic of the 15 cm x 25 cm test panels exposed at 30 m/s represents a far worse condition than normally would be encountered in most service applications.

The test panels were especially susceptible to edge failure because of the fashion in which they had to be mounted in the flow channel. At 30 m/s, the steel panels were precisely fitted into slots in the plexiglass sidewall of the channel. The wall was then masked and the coatings applied. While this procedure insured minimal edge mismatch and a smooth panel-to-wall transition, it didn't permit elimination of all edge holidays at the tight crevice created between the panel edge and the plexiglass. At the lower velocities (3 m/s thru 18 m/s), all panel edges were double-coated, but it is believed that some edge damage still occurred during installation. Thus, for the purpose of projecting velocity thresholds, this author tended to minimize the significance of coating damage close to the edge. Mindful of this assumption, it then does not seem unreasonable to propose that the velocity threshold for the MIL-P-24441 and TARSET epoxy coatings would exceed 30 m/s for the flow conditions and exposure period characteristic of this study.

To what extent beyond the $\simeq$ 900 hour exposure period these coatings would exhibit stable behavior (before gross failure occurs) is uncertain. However, extrapolation of the electrical impedance data for panels where edge failure was not a factor (e.g. see Figure 18) suggests that the coatings might have been stable for a significantly longer period than 900 hours. It would be unwise to attempt to relate directly these laboratory results obtained under a narrow set of experimental

conditions to probable performance on a high speed ship given the complex nature of the ship's duty cycle and much broader range of environmental conditions. However, the results of the study do provide some basis for arguing that some of the conventional marine coatings might, in fact, provide acceptable protection in selected areas of a high speed ship hull. Certainly, the conventional marine coatings cannot, as yet, be arbitrarily disregarded for all high velocity applications.

Probable Failure Mode

Although, because of the edge effect, the number of coating holidays per unit area of test panel tended to be more numerous than might be normally encountered in service, it is assumed that the actual coating holidays were physically not unlike those that would occur in service. Thus, while less significance was attached to edge-related failures in projecting velocity thresholds, the edge failures are believed to be quite significant for analyzing probable failure modes in parallel, high velocity seawater flow.

The first visual indication of coating failure (excepting the leading edge breakdown at 15 m/s) was blistering at different points near the edges on panels exposed at 30 m/s. There is not unanimous agreement on the mechanism underlying the formation of blisters in a barrier-type coating in seawater. However, the events generally associated with blister formation are as follows: (a) uptake or absorption of seawater by the coating due to osmotic forces; (b) seawater reorientation within the coating leading to the development of micropores where seawater exists in a continuous phase; (c) eventual development and/or migration of these seawater micropores through to the substrate/coating interface; (d) corrosion of the substrate either at a seawater-filled micropore or at a holiday where seawater has penetrated through the substrate; (e) formation of corrosion products which cause localized expansion stresses; (f) localized breakdown of the coating/substrate adhesive bond due to the combined action of corrosion and localized expansion stresses attributable to corrosion product formation and seawater osmosis. At 30 m/s, the experimental results suggest that the formation and development of macroscopic blisters are early stages of the overall damage process leading to gross coating disbondment. The results at the lower velocities provided little insight into probable failure modes under parallel flow since the only observed gross failure occurred on a leading edge subjected to impinging flow.

The experimental results do not provide any direct evidence as to the effect of flow velocity on the initial formation and/or the development of coating blisters. The fact that blistering was only detected at the highest velocity does not necessarily mean that the high flow velocity caused the blistering. As previously discussed, there were significant differences in the way the test panels at 30 m/s were mounted in the channel versus the panels at the lower velocities. It is believed that these differences gave rise to a greater number of edge holidays at the 30 m/s velocity and, therefore, better explain the occurrence of edge blistering at 30 m/s.

Hackworth et al[12] proposed a failure mode, dependent on blister formation, for coatings exposed to high velocity, non-cavitating flow. Hackworth hypothesized that, alone, the hydrodynamic shear stresses created in high velocity flow are much too low to cause gross coating failure. Using flow over a foil as an analog, he proposed that blisters might give rise to lifting forces of much higher magnitude that could rupture the coating. Although the subject study does not provide direct evidence to support Hackworth's proposed failure mode, in the opinion of the author, the proposed failure mode merits consideration.

In general conformance with Hackworth's proposed failure mode, Figure 31 presents a simplified picture of the forces that might arise about a blister and how the coating might ultimately respond to such forces. As shown, two mutually perpendicular forces — lift and pressure drag — are distributed over the surface of the blister. The pertinent equations from airfoil theory describing these forces are as follows:

$$(1)\ F_L = 1/2 C_L A \rho V^2$$

$$(2)\ F_D = 1/2 C_D A \rho V^2$$

where,

F_L = lift force

F_D = pressure drag force

C_L = lift coefficient

C_D = drag coefficient

A = maximum projected area

ρ = density of fluid

V = velocity

A lifting force would create a differential pressure across the coating at the point of the blister. The situation would be somewhat analogous to the action of a plumber's helper (suction-type plunger). As the coating is lifted from the substrate, it would tend to create a vacuum in the area between the coating and substrate. The resulting differential pressure would accelerate seawater transport through the coating at the blister. The additional volume of seawater entering the blister would increase corrosion of the substrate leading to further breakdown of the adhesive bond and increase expansion stresses from corrsion product formation. Under the combined action of these forces, the blister would continue to grow. Ultimately, the blister reaches a critical size such that the hydrodynamic forces are resolved causing a tensile stress in the coating that exceeds its inherent tensile strength and gross rupture occurs.

In order to get a feel for the relative magnitude of the forces that might be developed in this fashion, it is worthwhile to consider an example. Assuming a spherical-like blister, approximately .4 mm high and 6 mm in diameter, the resulting lift and drag forces can be estimated as follows:

(1) Lift Force

$$F_L = 1/2 C_L A \rho V^2$$

where,

$$C_L = 20\ h/d^* = (20)\ (.4 \div 6) = 1.33$$
$$A = \pi (d/2)^2 = \pi (3)^2 = 28.27\ mm^2 = 2.83 \times 10^{-5}\ m^2$$
$$\rho \simeq 1000\ kg/m^3$$
$$V = 30\ m/s$$

$$F = (1/2)\ (1.33)\ (2.83 \times 10^{-5})\ (1000)\ (30)^2$$
$$F_L = 16.9\ \text{newtons}$$

(2) Pressure Drag Force

$$F_D = 1/2 C_D A \rho V^2$$

where,

$C_D \simeq .4$ (from Streeter[13])
$$A = 2.83 \times 10^{-5}\ m^2$$
$$\rho \simeq 1000\ kg/m^3$$
$$V = 30\ m/s$$

*$C_L = 20\ h/d$, for $h/d < .07$ from reference (12).

$$F_D = 5.09 \text{ newtons}$$

The resultant of these two forces is 17.6 newtons

If it is assumed that the resultant hydrodynamic load creates a tensile stress in the coating distributed about the perimeter of the blister somewhat like shown in Figure 32, then a rough approximation of the coating area over which the applied load is distributed is ½ x circumference of blister x coating thickness. Using the dimensions of the blister assumed above, the cross-sectional area is calculated as follows:

$$A = \tfrac{1}{2} \times \pi .006 \times .000254 = 2.39 \times 10^{-6} \text{ m}^2$$

Then, as a rough approximation, the resulting tensile stress in the coating is:

$$\begin{aligned} \sigma &= F \div A \\ &= 17.6 \div 2.39 \times 10^{-6} \\ \sigma &= 7350000 \text{ newtons/m}^2 = 7350 \text{ Kpa} \end{aligned}$$

The reported tensile strength* of the TARSET Epoxy coating is 6900 Kpa. Adhesion measurements using an Elcometer Model 106 Adhesion Tester gave values of bond strength for all three coatings that ranged between 7,000 to 14,000 Kpa. Thus, as a first approximation, it appears that lifting forces sufficient to rupture the protective coating could be developed at blisters.

In comparison, the calculated shear stresses exerted by the fluid on the coating are significantly lower. At 30 m/s, the shear stress is calculated to be $\simeq$ 1.64 Kpa from the following equation:

$$\tau = .029\, \rho\, V^2\, (1/Re)^{.2}$$

where,

$$\begin{aligned} \tau &= \text{shear stress} \\ \rho &= \text{density} \\ V &= \text{velocity} \\ R_e &= \text{Reynolds Number} = \frac{V4R}{\nu} \\ \nu &= \text{kinematic viscosity} \\ R &= \text{hydraulic radius} = A/P \text{ for a rectangular channel} \\ A &= \text{cross-section area of channel} \\ P &= \text{wetted perimeter of channel} \end{aligned}$$

Over an area the size of the blister, this represents an applied load of $\simeq$ .046 newtons which is $\simeq$ 1/400 of the load calculated for lift and pressure drag. The relative magnitude of the forces estimated from theoretical consideration lends credibility to Hackworth's proposed failure mode. It should be re-emphasized that all observed coating disbondment at 30 m/s was preceded by blistering.

The subject study does not provide experimental verification of Hackworth's model. However, the way in which coating failure was observed to occur certainly fits within the framework of Hackworth's model. It would appear that further work is deserving to experimentally verify this model.

Hydromechanical Wear

The experimental results showed that the applied dry film thickness of the coatings remained essentially constant during the velocity tests. In the past, there has been conjecture by many investigators, including this author, that hydromechanical wear or erosion could become a factor at the higher seawater velocities. However, the lack of significant reduction in the dry film thickness suggests that hydromechanical wear might not be a factor over the velocity range investigated under

*Porter Co. Product Data Sheet A8089 (9/75)

conditions of parallel flow. Again, one must guard against drawing too broad of a conclusion from the limited data. Different coatings and/or a longer exposure period might have yielded different results.

Electrical Impedance Measurements

The experimental results demonstrated the utility of electrical impedance measurements as a non-destructive technique for detecting impending failure of non-conductive, barrier-type coatings. Throughout the study, measured changes in coating resistance and capacitance correlated excellently with observed coating performance.

Electrical impedance data also provides a quantitative basis for ranking coating performance. When coatings are rated strictly by visual inspection, there is always a judgement factor depending on the individual making the inspection. It would seem that, with some modification of technique, the use of electrical impedance measurements could be extended to actual service situations. For example, the data might facilitate better judgement as to the condition of a protective coating on a structure and when recoat might be necessary.

Parallel Versus Impingement Or Cavitation-Type Flow

There is little direct evidence from the subject study to indicate that, at the higher velocities, parallel flow is significantly less damaging than impingement or cavitation-type flow. However, comparison of these results with the results of other work conducted under different types of flow tend to strengthen this supposition.

In the present study, the results obtained at 15 m/s provided the only indication as to the relative severity of different types of flow. Coating failure occurred almost immediately on the one panel subjected to impingement and cavitation-type flow (at the leading edge). The remaining panels not exposed to leading edge impingement and cavitation exhibited negligible coating deterioration over the 812-hour test period. At the lower velocities (12 m/s thru 3 m/s), impingement-type flow on the leading edge did not cause detectable coating damage. The panels exposed at 30 m/s and 18 m/s were not subjected to impingement or cavitation-type flow.

Lichtman and Kallas[4] reported failures beginning after only 1 hour for vinyl-coated specimens exposed to cavitating flow at $\simeq$28 m/s in a high speed nozzle apparatus. In the subject program, the first failure at 30 m/s was not observed until $\simeq$ 54 hours of exposure.

In other work using a rotating disk apparatus, Lichtman et al [1] reported significant volume loss of teflon and polyvinyl chloride materials after 10 hours of cavitating flow at $\simeq$30 m/s. In the subject study, two of the three epoxy-type coatings exhibited minimal volume loss after 898 hours exposure at 30 m/s.

The Bureau of Reclamation[1] conducted water tunnel tests on various coatings applied to conical-type steel specimens, subjected to both impingement and cavitating flow at $\simeq$20 m/s. They reported gross failure of vinyl coatings in less than 10 hours test time. Thus, based on a comparison of other work, there is some supportive evidence suggesting that, at high velocities, parallel flow is not as damaging to coating materials as impingement or cavitation-type flow. This conclusion has been implied indirectly quite often in the literature but little data has been offered to substantiate it.

V. CONCLUSIONS

1. Neglecting edge-related damage, the results suggest the velocity threshold for the MIL-P-24441 Epoxy and TARSET Epoxy exceeds 30 m/s under the flow conditions and time period characteristic of the study. It would be unrealistic to attempt to extrapolate these results to actual service situations. The results do provide an indication, however, that some marine epoxy coatings might be serviceable at velocities approaching 30 m/s, depending on the character of flow.

2. Under the given set of high velocity conditions, blister formation appears to be a critical part of the coating failure process. Hackworth proposed a failure mode, dependent on blister formation, that deserves consideration and appears to justify further experimental study.

3. Under the given set of high velocity conditions, hydromechanical wear was negligible.

4. Electrical impedance measurements can be used to detect impending coating failure. These measurements also provide a quantitative basis of ranking coating performance.

5. In the velocity range between 15 and 30 m/s, the experimental results provide some evidence, both direct and indirect, that parallel flow is not as damaging as impingement or cavitation-type flow.

VI. REFERENCES

1. J. Z. Lichtman, D. H. Kallas, C. K. Chatten, and E. P. Cochrane, Jr. Trans. ASME, August, 1958, p. 1325-1341.

2. J. Z. Lichtman, D. H. Kallas, C. K. Chatten, and E. P. Cochrane, Jr., Corrosion, Vol. 17, October, 1961.

3. A. E. Hohman and W. L. Kennedy, Materials Protection, September, 1963.

4. J. Z. Lichtman and D. H. Kallas, Materials Protection, April, 1967.

5. A. Thiruvengadam and A. F. Conn, Materials Research and Standards, March, 1972.

6. G. W. Kelly, "Improved Cavitation Damage Resistant Coatings For Surface Effect Ships", Final Report prepared for U.S. Navy SES Project office by LTV Aerospace under Contract No. 1-35544, July, 1973.

7. Q.L. Morris, "Surface Effect Ship Coatings Development and Seal Material Evaluation", Final Report prepared for U.S. Navy SES Project office by Vought Corp. under Contract No. N00024-75-C-5092, February, 1977.

8. F. Wormwell and D. M. Brasher; J. Iron Steel Inst., 164, 141 (1950).

9. D. M. Brasher and A. H. Kingsbury; J. Appl. Chem., 4, 62 (1954).

10. H. C. O'Brien; Ind. Eng. Chem., 58, 45 (1966).

11. H. Leidheiser, Jr. and R. E. Touhsaent; Corrosion, 28, 435 (1972).

12. J. V. Hackworth, P. K. Conn, I. C. Snell; "An Investigation of Methods to Reduce or Eliminate Cavitation Erosion of Ship Propellers", U.S. Maritime Administration Report No. MA-RD-920-77085, June, 1977.

13. V. L. Streeter; Fluid Mechanics, 3rd edition, McGraw-Hill, New York, 1962.

TABLE I - SEAWATER CHEMISTRY DURING VELOCITY STUDIES

	Maximum	Minimum	Average
Salinity, ppm	34,200	29,600	32,500
pH	8.2	7.8	7.9
Temperature, °C	33	15	22
Dissolved Oxygen, ppm	8.1	5.0	6.9
Turbidity, J.T.U.	22	2.3	6

ACKNOWLEDGEMENT

The author gratefully acknowledges the financial support of the office of Naval Research under the project supervision of Dr. P. A. Clarkin; and the cooperation and assistance of Mr. R. J. Goode and Mr. M. L. Peterson, Naval Research Laboratory, with whom much of this work was coordinated.

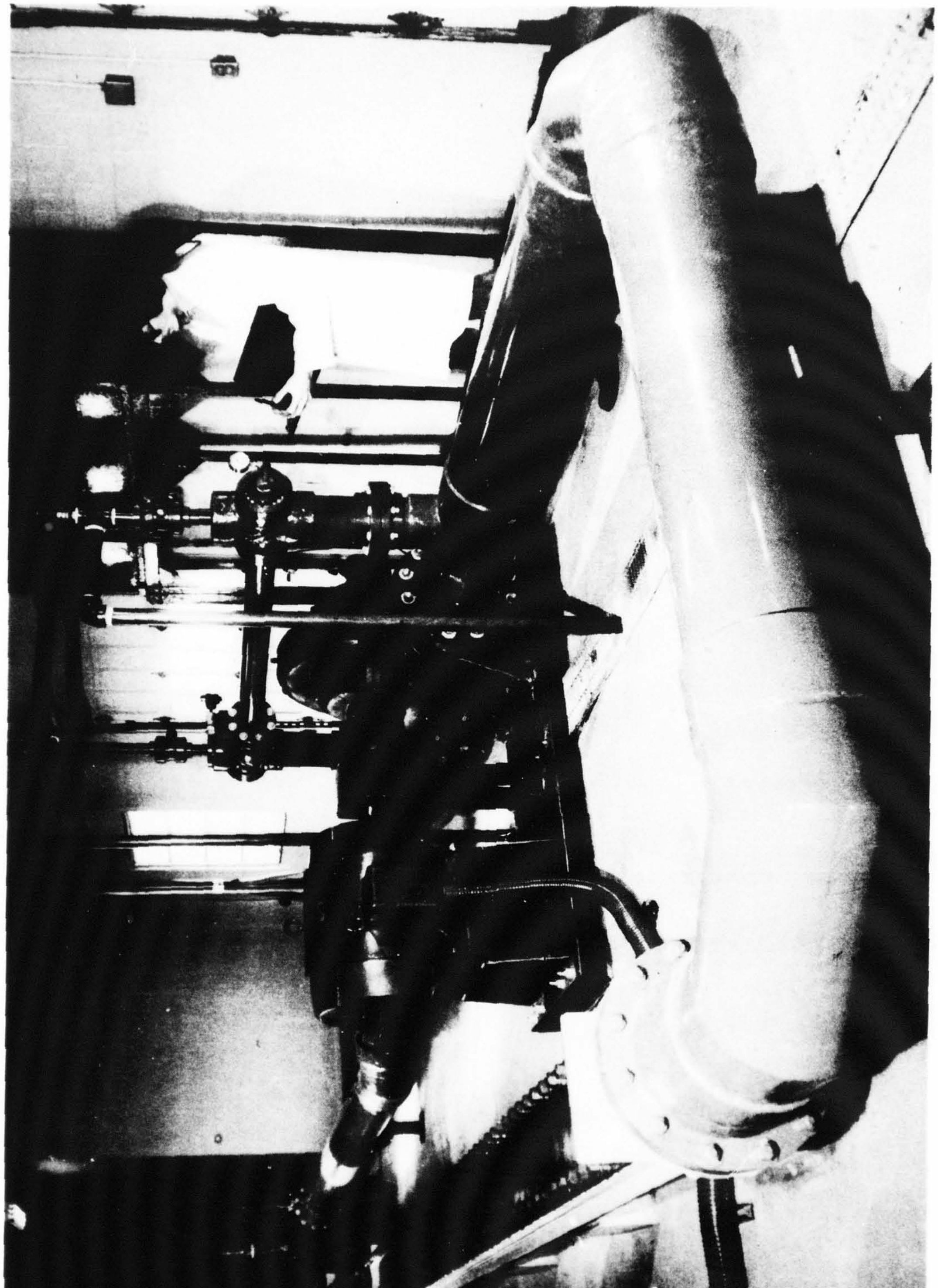


Figure 1 - High Velocity Flow Channel

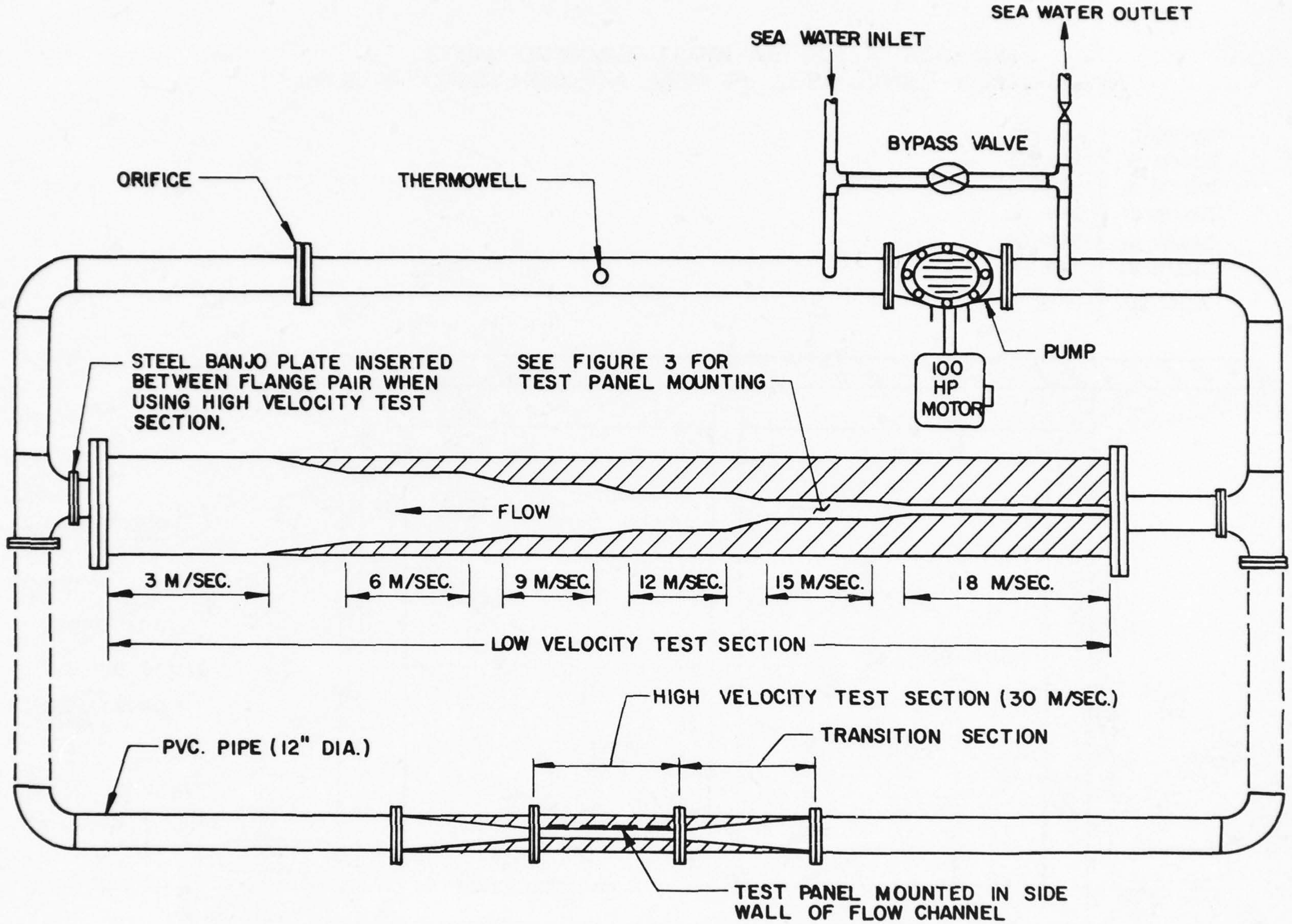
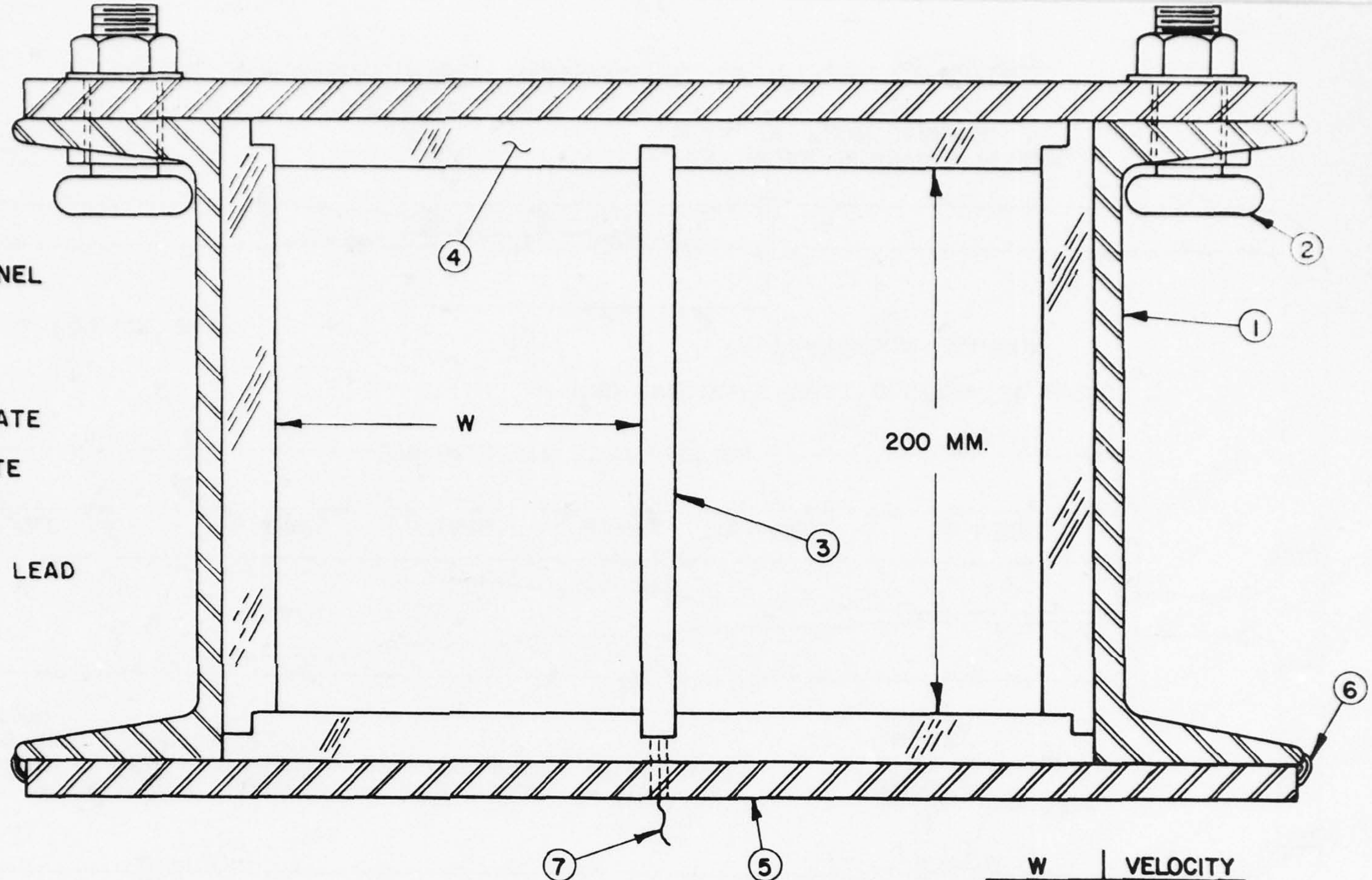


FIGURE 2—SIMPLIFIED SCHEMATIC OF FLOW CHANNEL

1	STEEL CHANNEL
2	T-BOLT
3	TEST PANEL
4	ACRYLIC PLATE
5	STEEL PLATE
6	WELD
7	ELECTRICAL LEAD CONNECTION



W	VELOCITY
50 MM.	18 M/SEC.
60 MM.	15 M/SEC.
75 MM.	12 M/SEC.
100 MM.	9 M/SEC.
150 MM.	6 M/SEC.
300 MM.	3 M/SEC.

FIGURE 3 - CROSS-SECTION VIEW OF TEST PANEL MOUNTED IN FLOW CHANNEL (LOW VELOCITY SECTION)

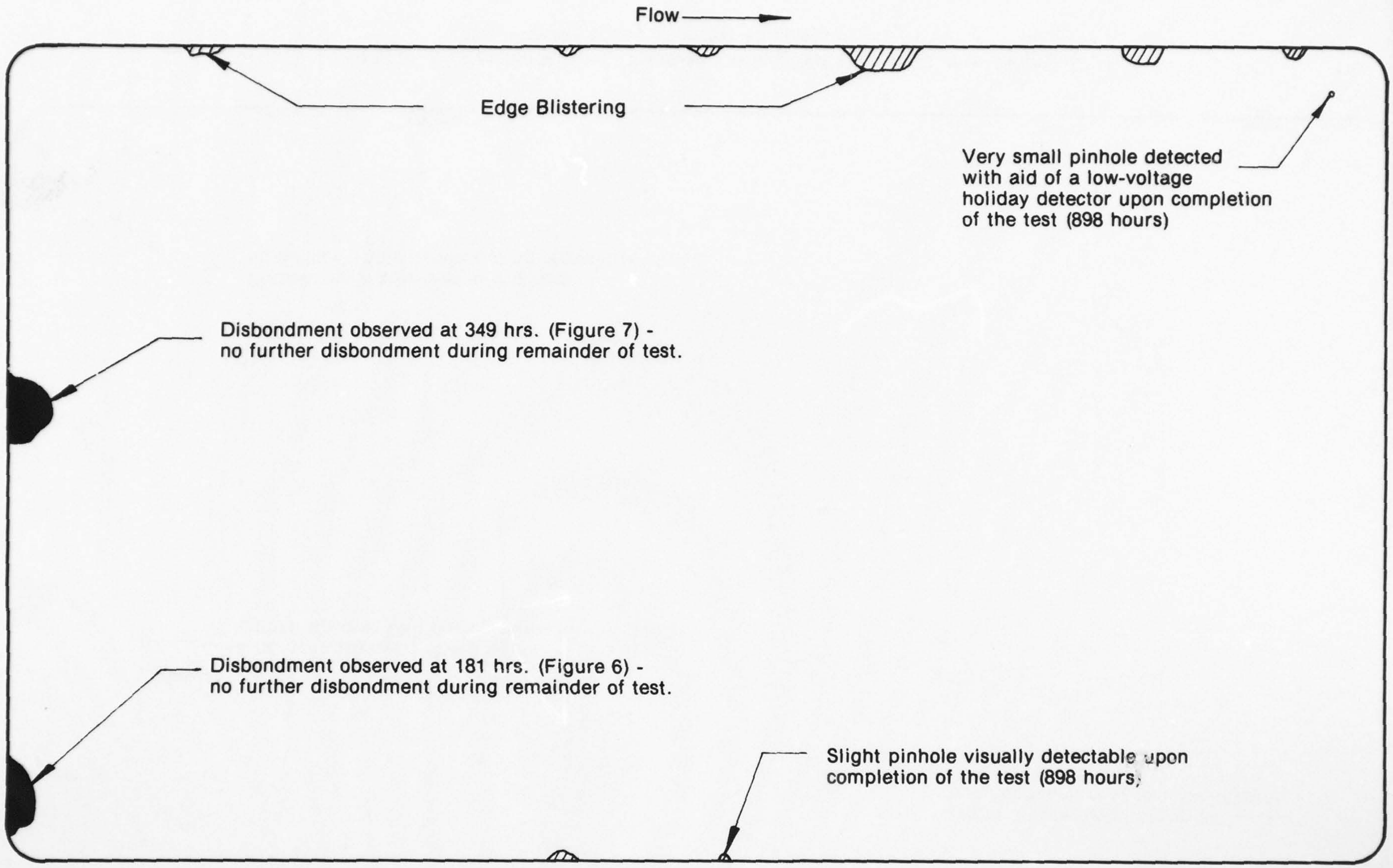


Figure 4 - Coating Failure Observed During Test Run at 30 m/s - Panel #1; MIL-P-24441 Epoxy (Approx. to Scale)

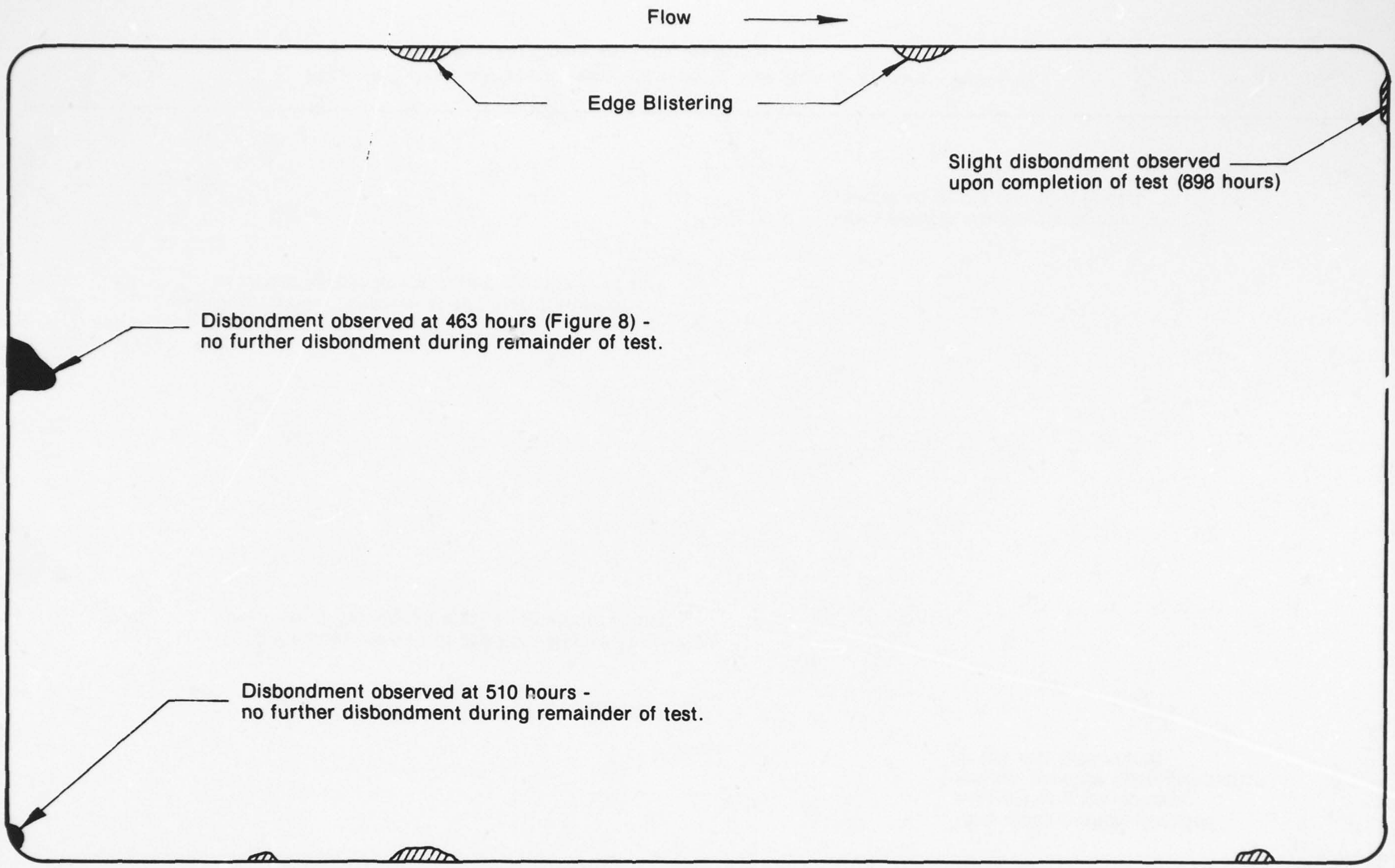


Figure 5 - Coating Failure Observed During Test Run at 30 m/s - Panel #2; MIL-P-24441 Epoxy (Approx. To Scale)

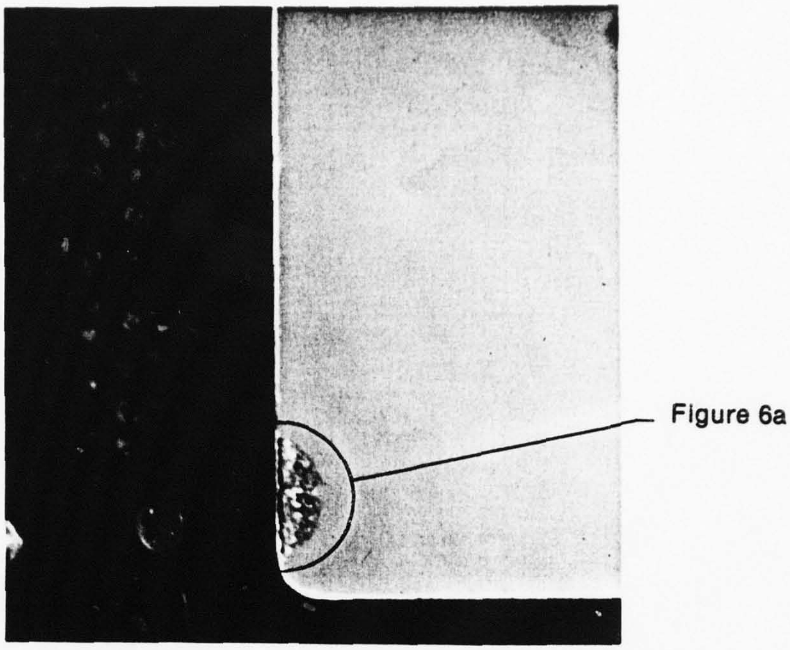


Figure 6 - Coating Disbondment Observed at 181 Hours at 30 m/s - Panel #1; MIL-P-24441 Epoxy.

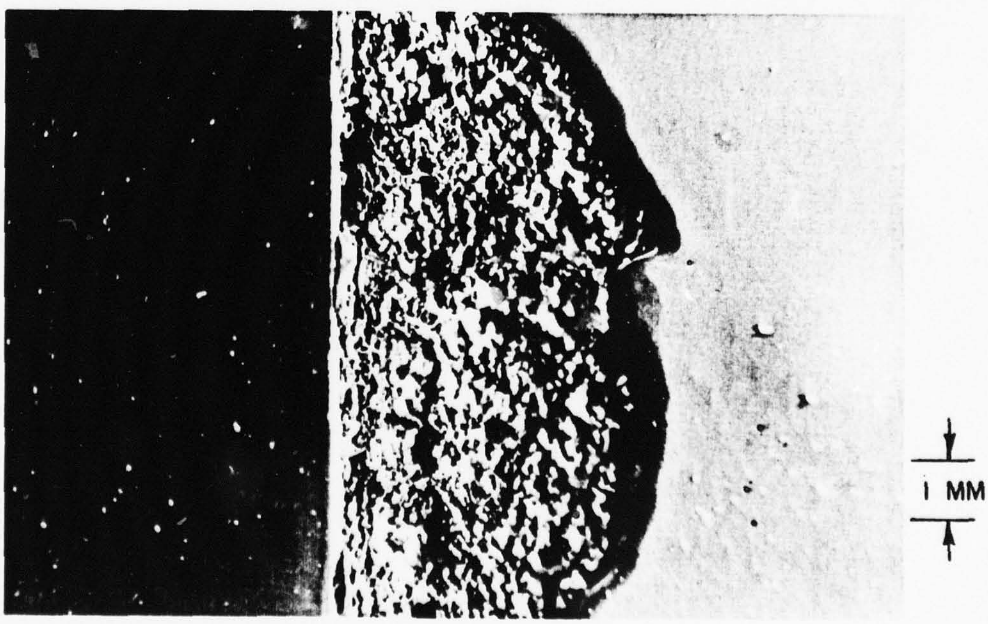


Figure 6a - Close-Up of Coating Holiday After 898 Hours - Panel #1.

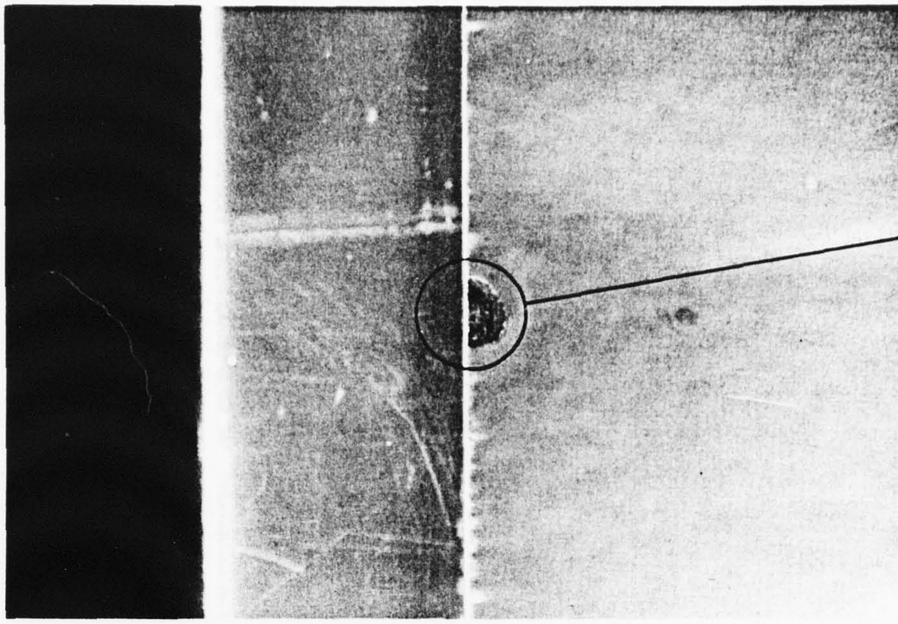


Figure 7 - Coating Disbondment Observed At 349 Hours at 30 m/s - Panel #1; MIL-P-24441 Epoxy

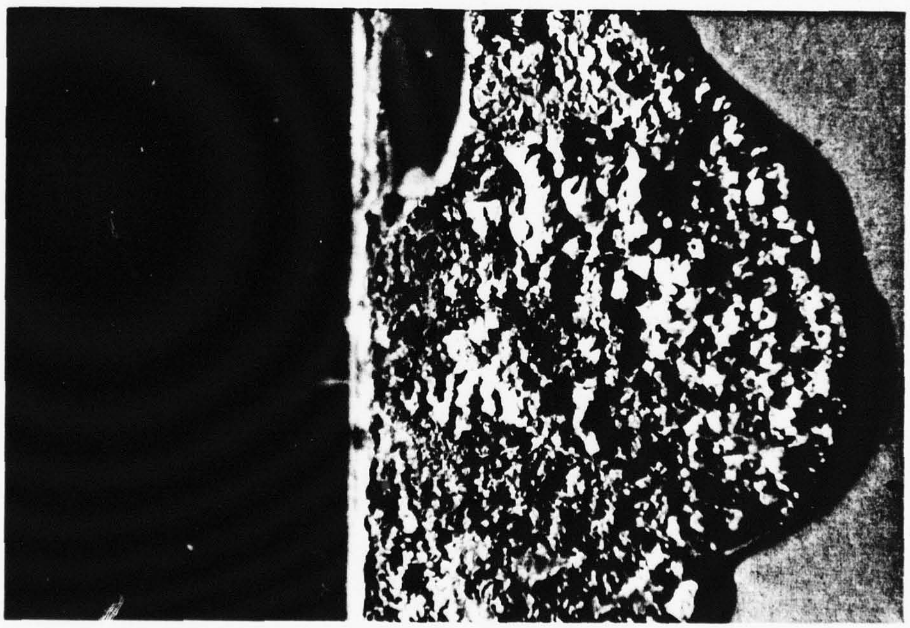


Figure 7a - Close-Up of Coating Holiday After 898 Hours - Panel #1

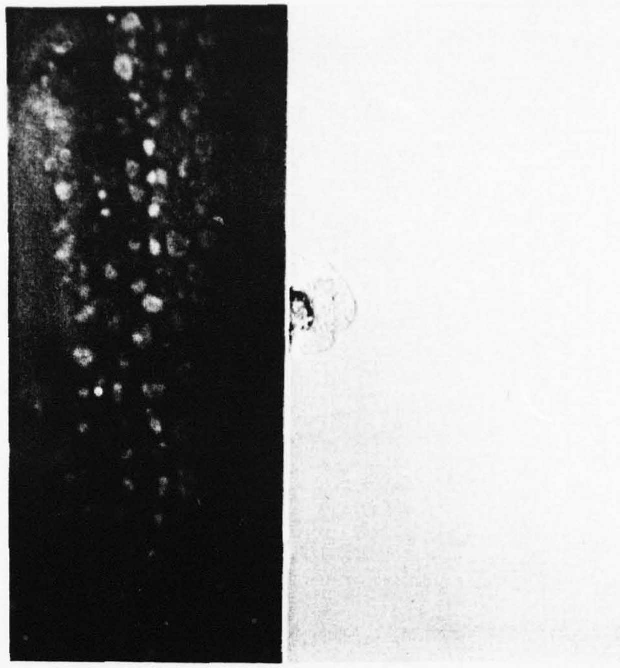


Figure 8 - Coating Disbondment Observed At 463 Hours at 30 m/s - Panel #1; MIL-P-24441 Epoxy

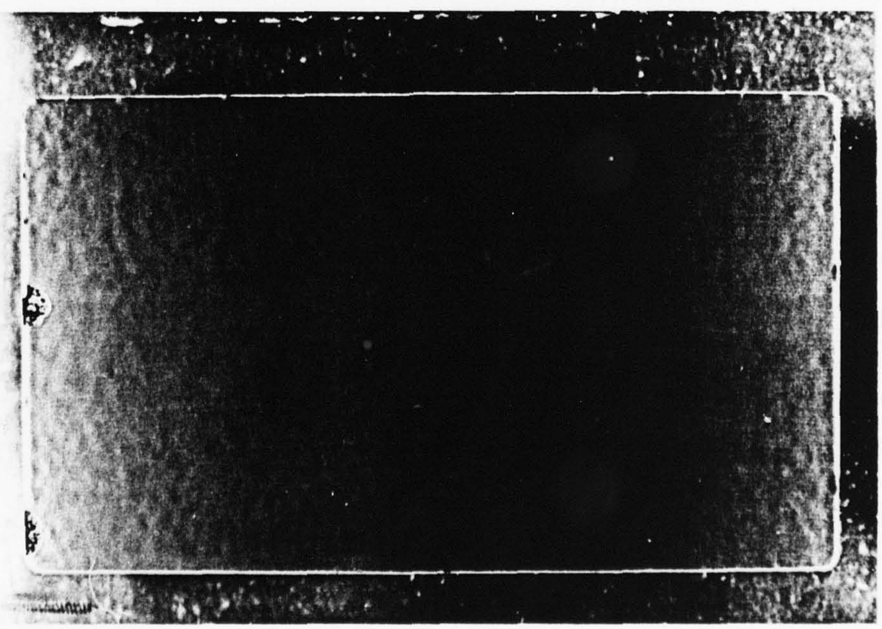


Figure 9 - MIL-P-24441 Epoxy After 898 Hours Exposure to Seawater Flowing At 30 m/s (Panel #1)

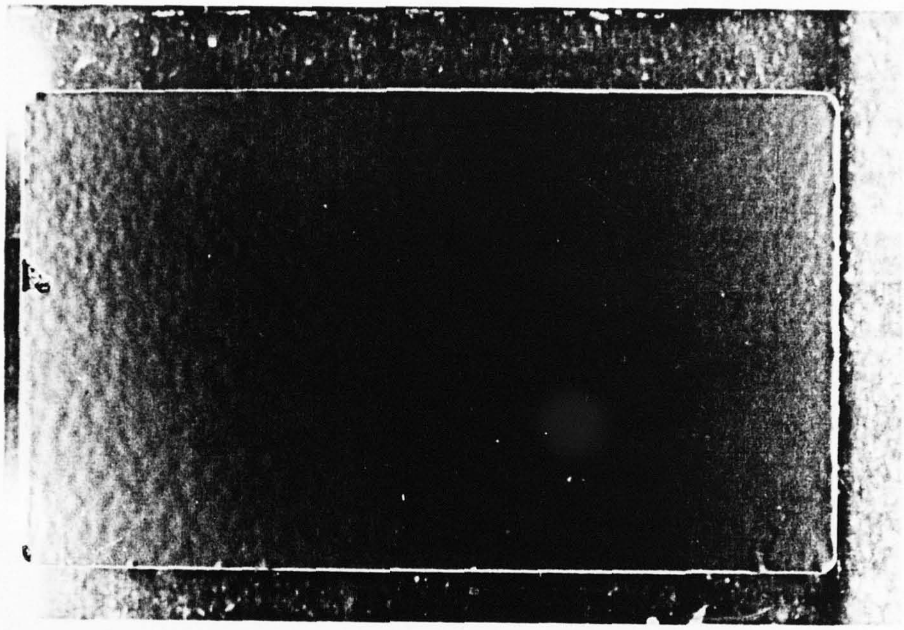


Figure 10 - MIL-P-24441 Epoxy After 898 Hour Exposure to Seawater Flowing At 30 m/s (Panel #2)

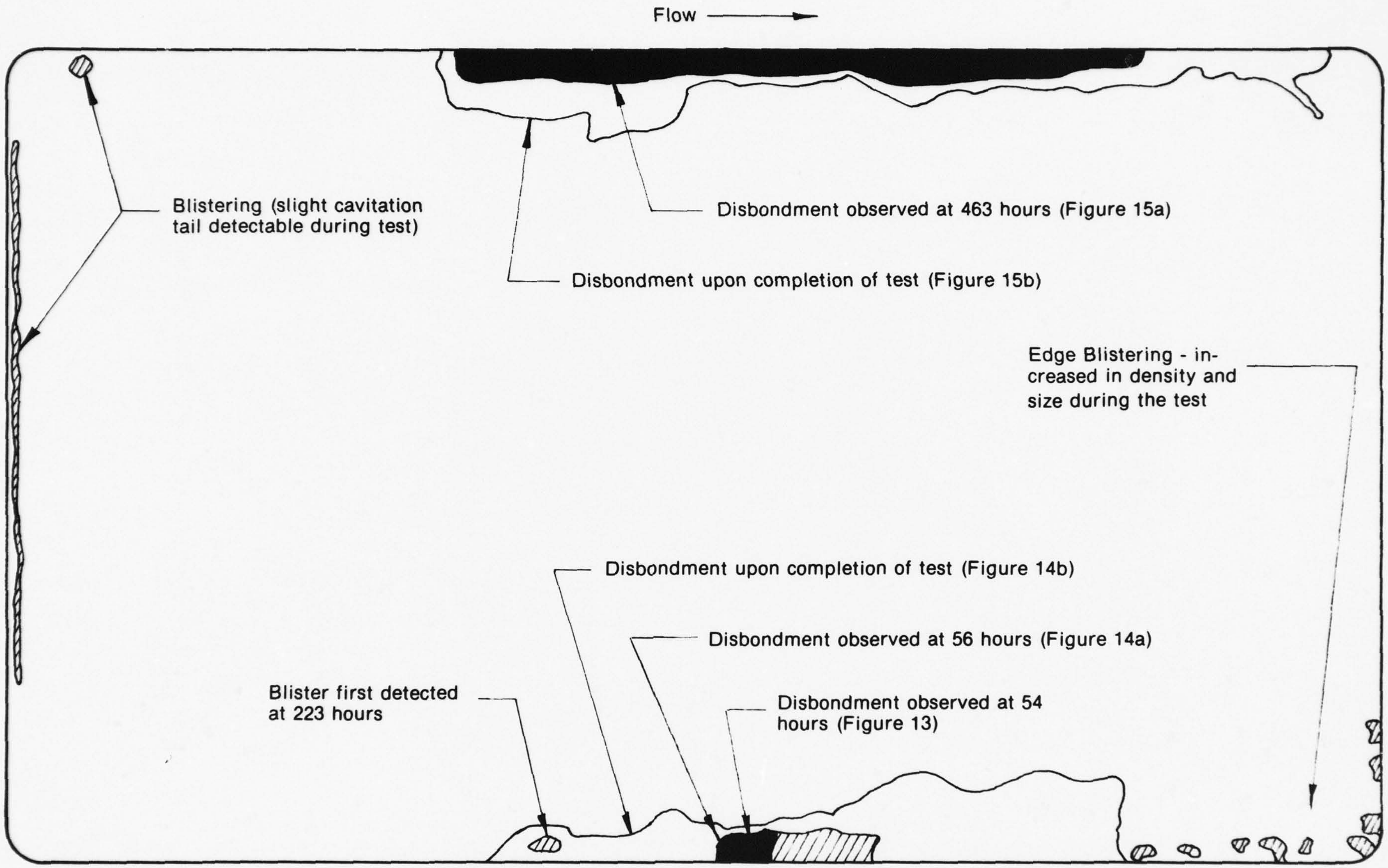


Figure 11 - Coating Failure Observed During Test Run at 30 m/s - Panel #3; DEVRAN Epoxy (Approx. To Scale)

cavitation
occuring at
blister in
coating

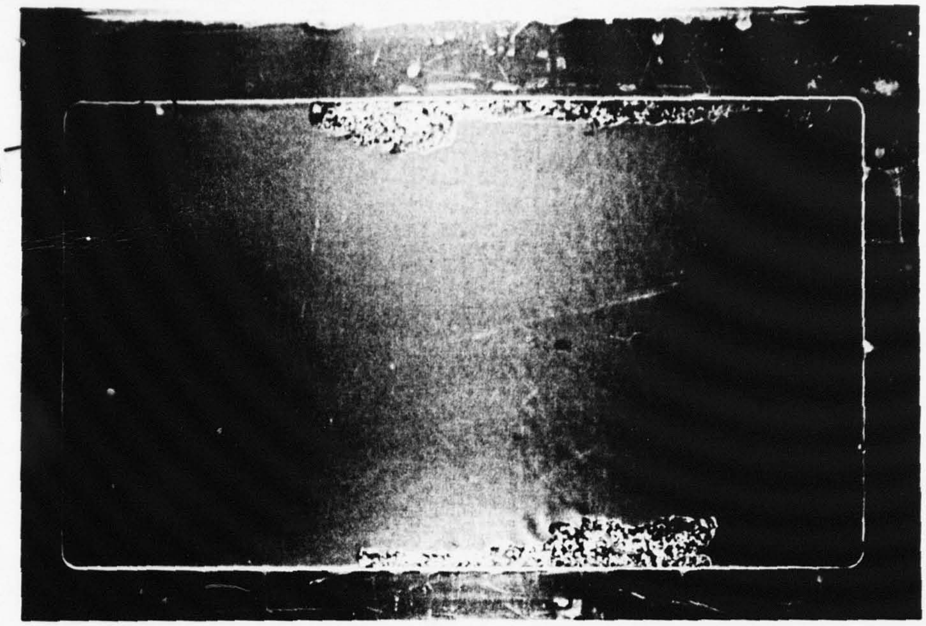


Figure 12 - DEVRAN Epoxy At 898 Hours Exposure to Seawater Flowing At 30 m/s

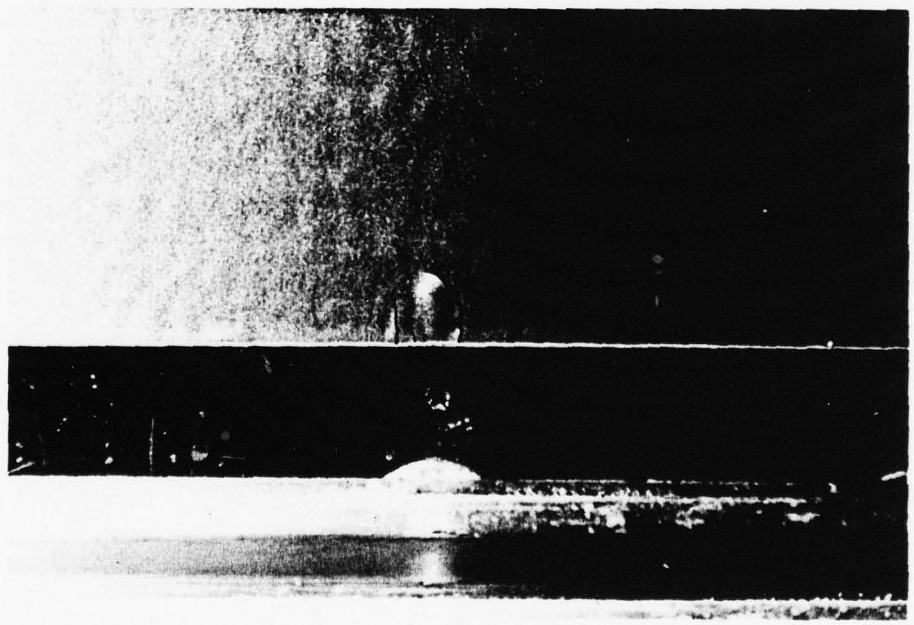
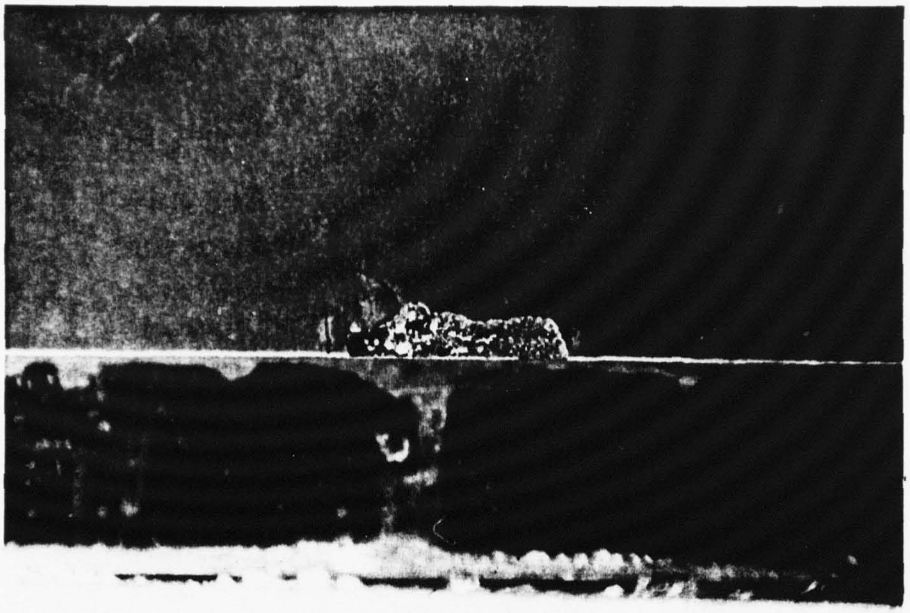
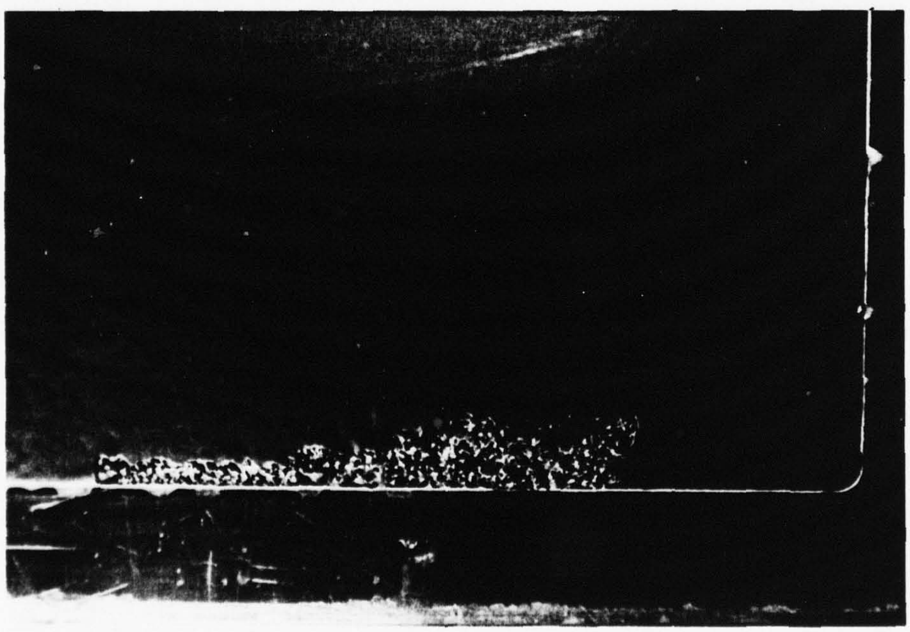


Figure 13 - Coating Disbondment Observed at 54 Hours at 30 m/s - Panel #3; DEVRAN Epoxy

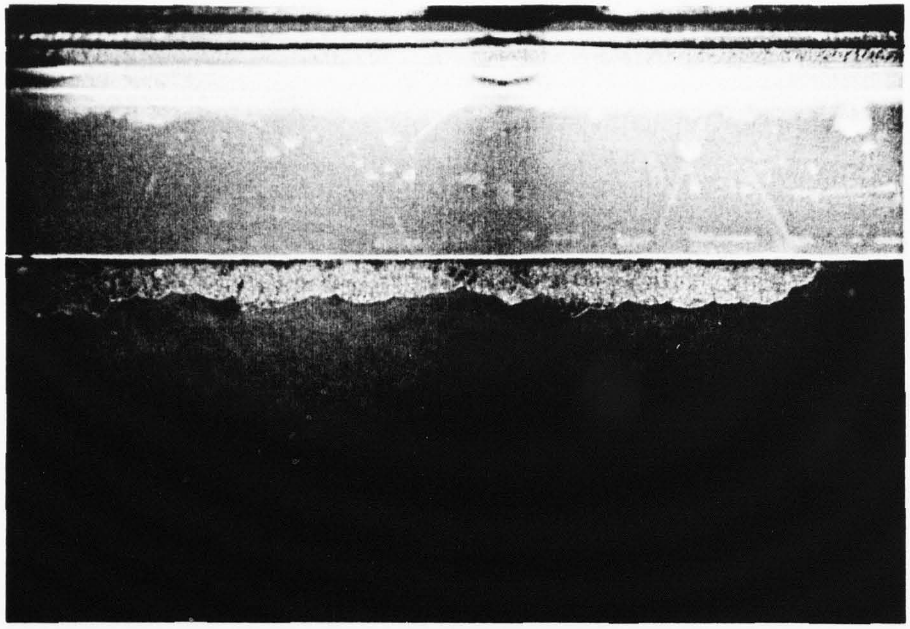


a. 56 Hours

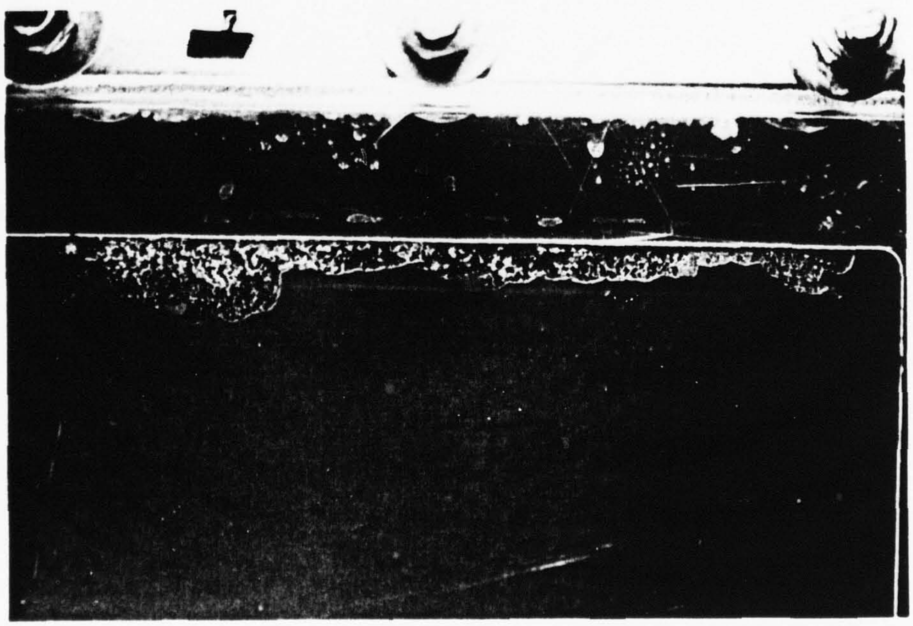


b. 463 Hours

Figure 14 - Development of Coating Holiday With Time - Panel #3; DEVRAN Epoxy at 30 m/s (Lower Edge of Panel)



a. 463 Hours



b. 898 Hours

Figure 15 - Development of Coating Holiday With Time - Panel #3; DEVRAN Epoxy at 30 m/s (Upper Edge of Panel)

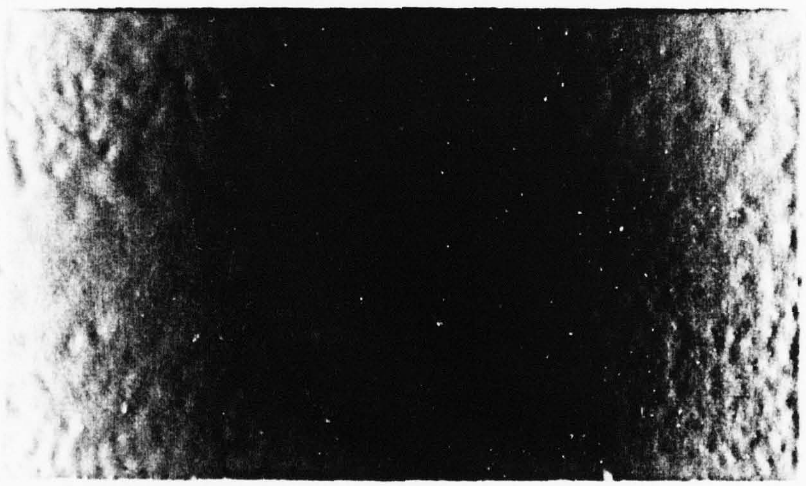


Figure 16 - Panel #4 TARSET Epoxy After 898 Hours Exposure to Seawater Flowing At 30 m/s

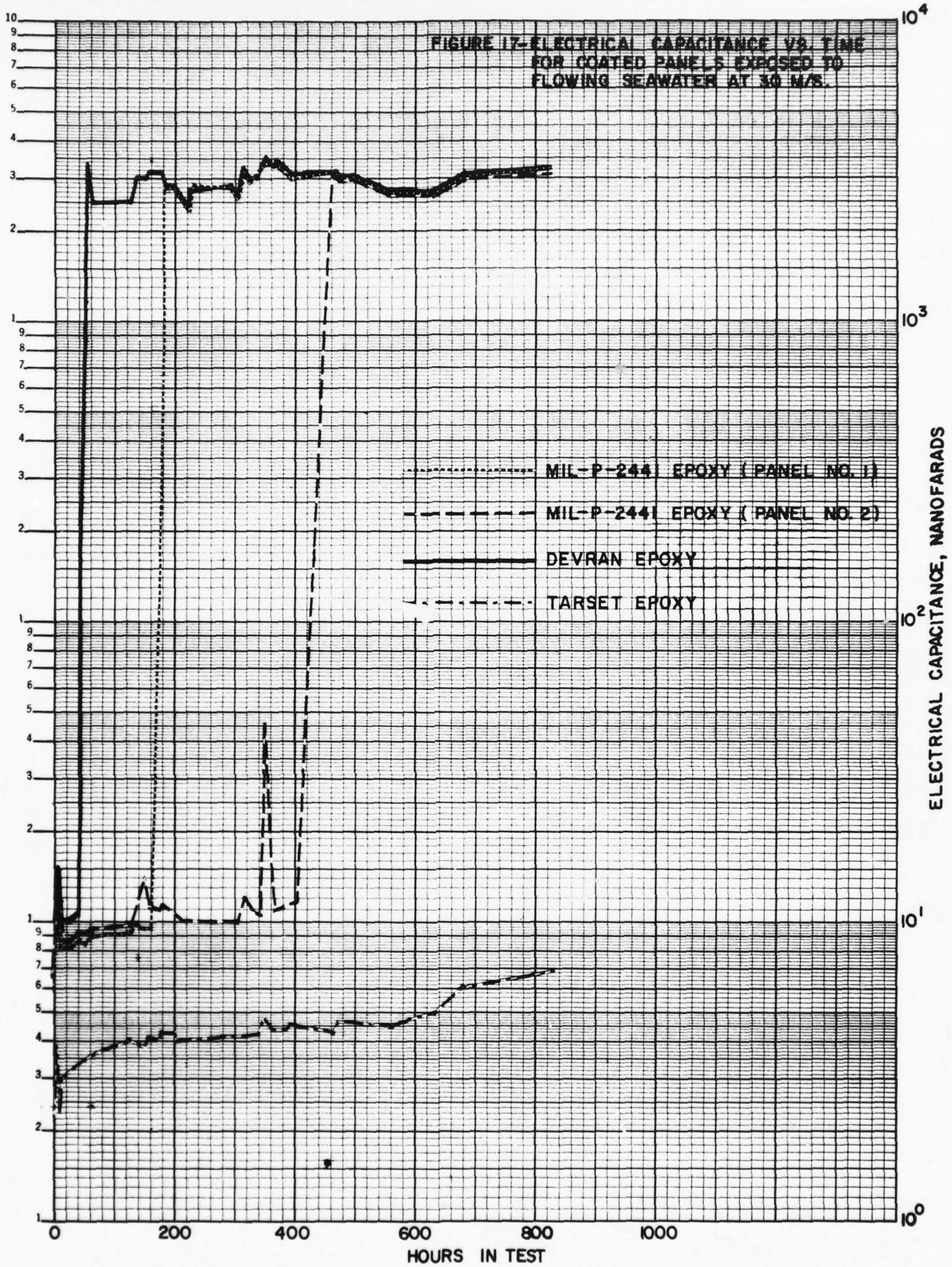


FIGURE 17-ELECTRICAL CAPACITANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 30 M/S.
MIL-P-2441 EPOXY (PANEL NO. 1)
MIL-P-2441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY
TARSET EPOXY
0
200
400
600
800
1000
HOURS IN TEST
10^0
10^1
10^2
10^3
10^4
ELECTRICAL CAPACITANCE, NANOFARADS

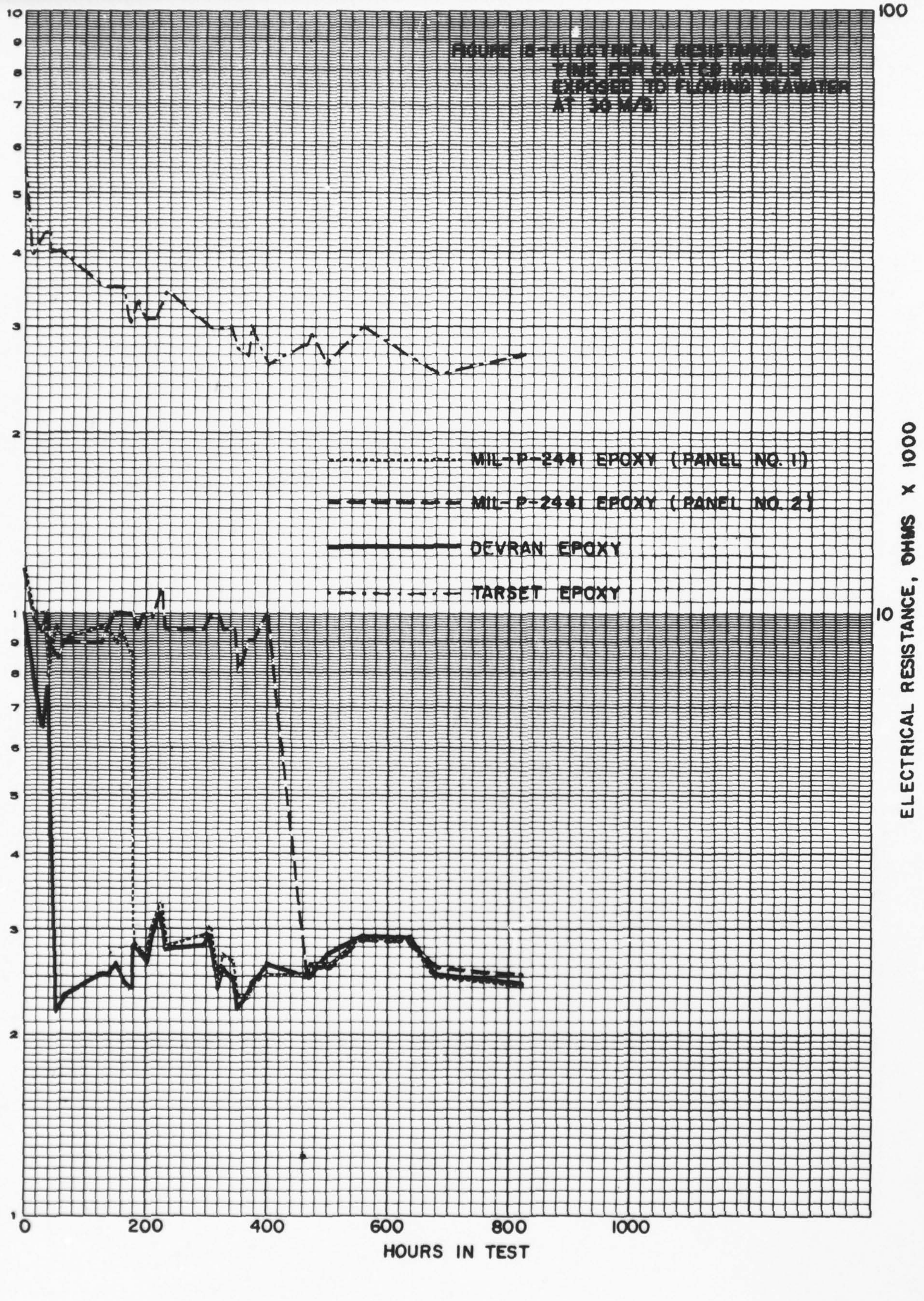


FIGURE 15-ELECTRICAL RESISTANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 30 M/S.

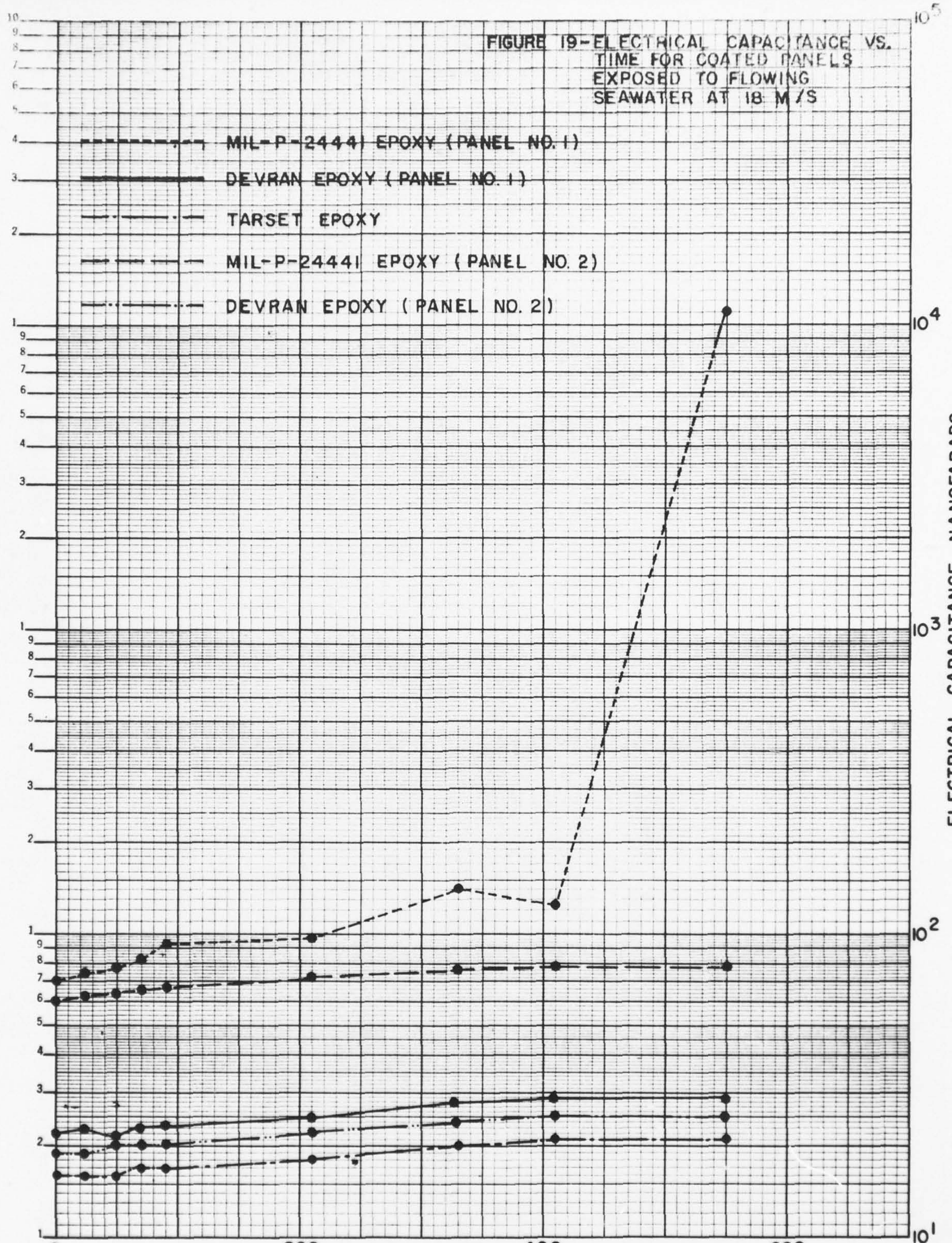


FIGURE 19-ELECTRICAL CAPACITANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 18 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
ELECTRICAL CAPACITANCE, NANOFARADS
HOURS IN TEST
0
200
400
600
10^1
10^2
10^3
10^4
10^5

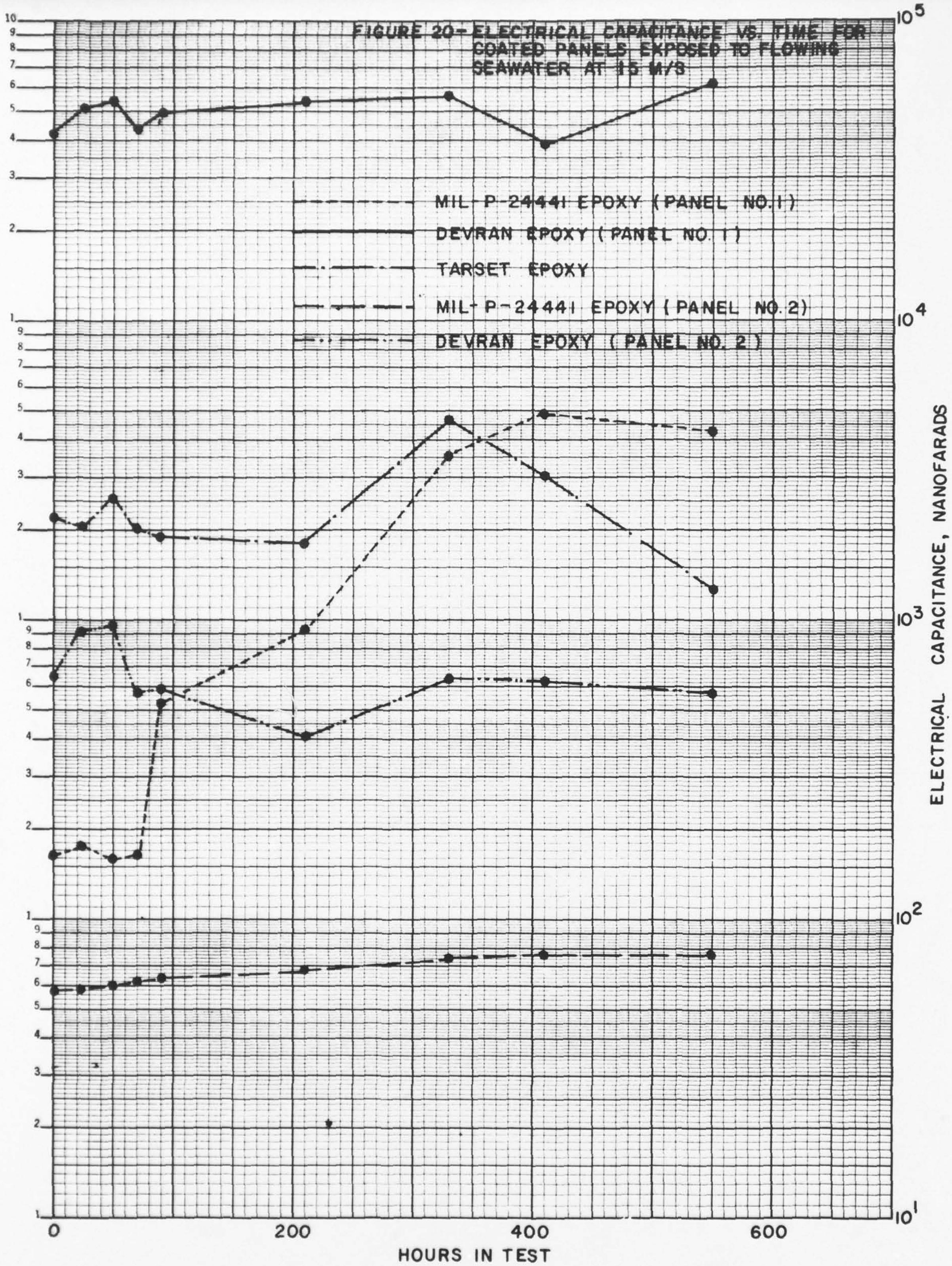


FIGURE 20 - ELECTRICAL CAPACITANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 15 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
0
200
400
600
HOURS IN TEST
ELECTRICAL CAPACITANCE, NANOFARADS

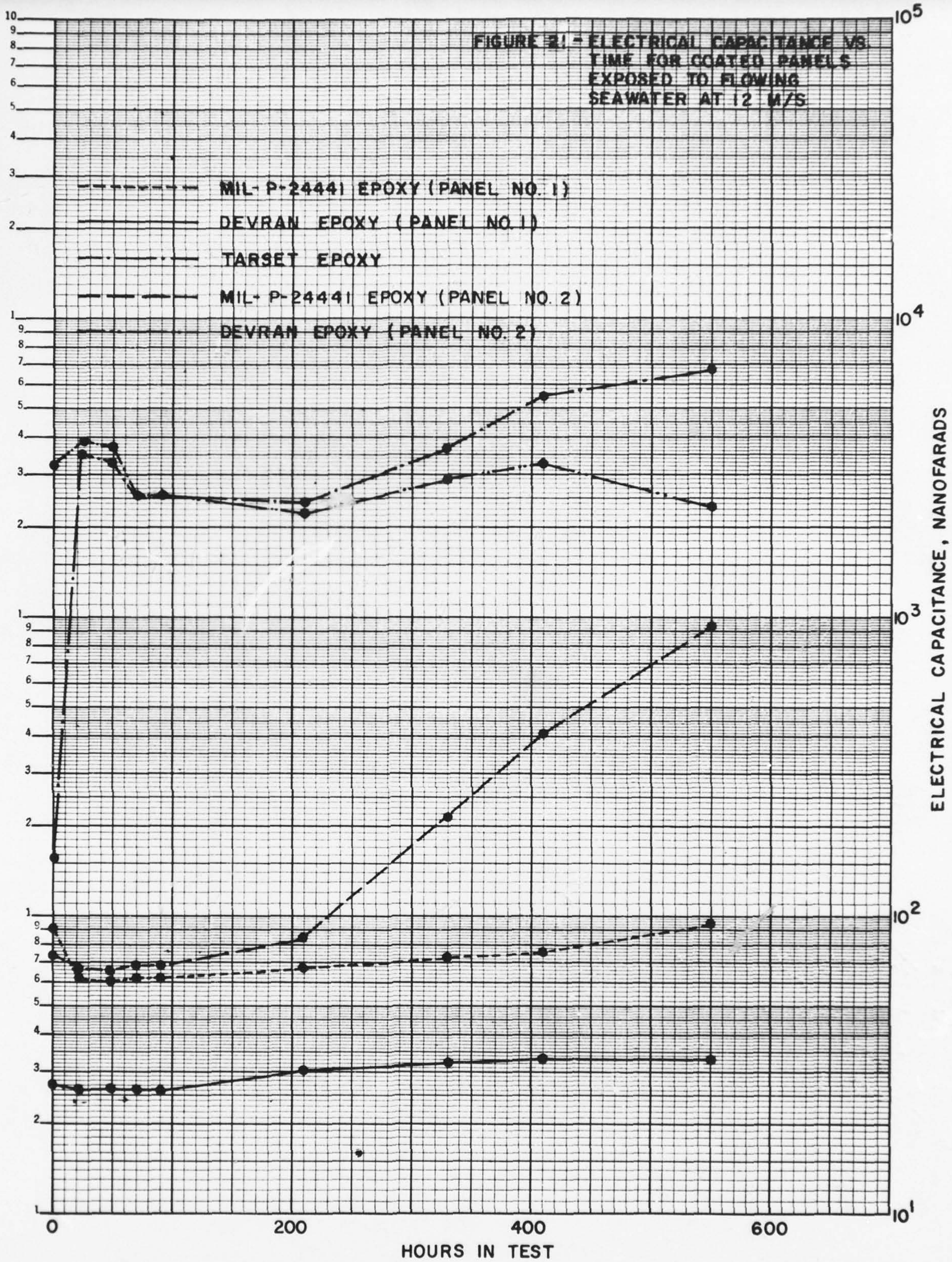


FIGURE 21 - ELECTRICAL CAPACITANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 12 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
ELECTRICAL CAPACITANCE, NANOFARADS
HOURS IN TEST
0
200
400
600
10^1
10^2
10^3
10^4
10^5

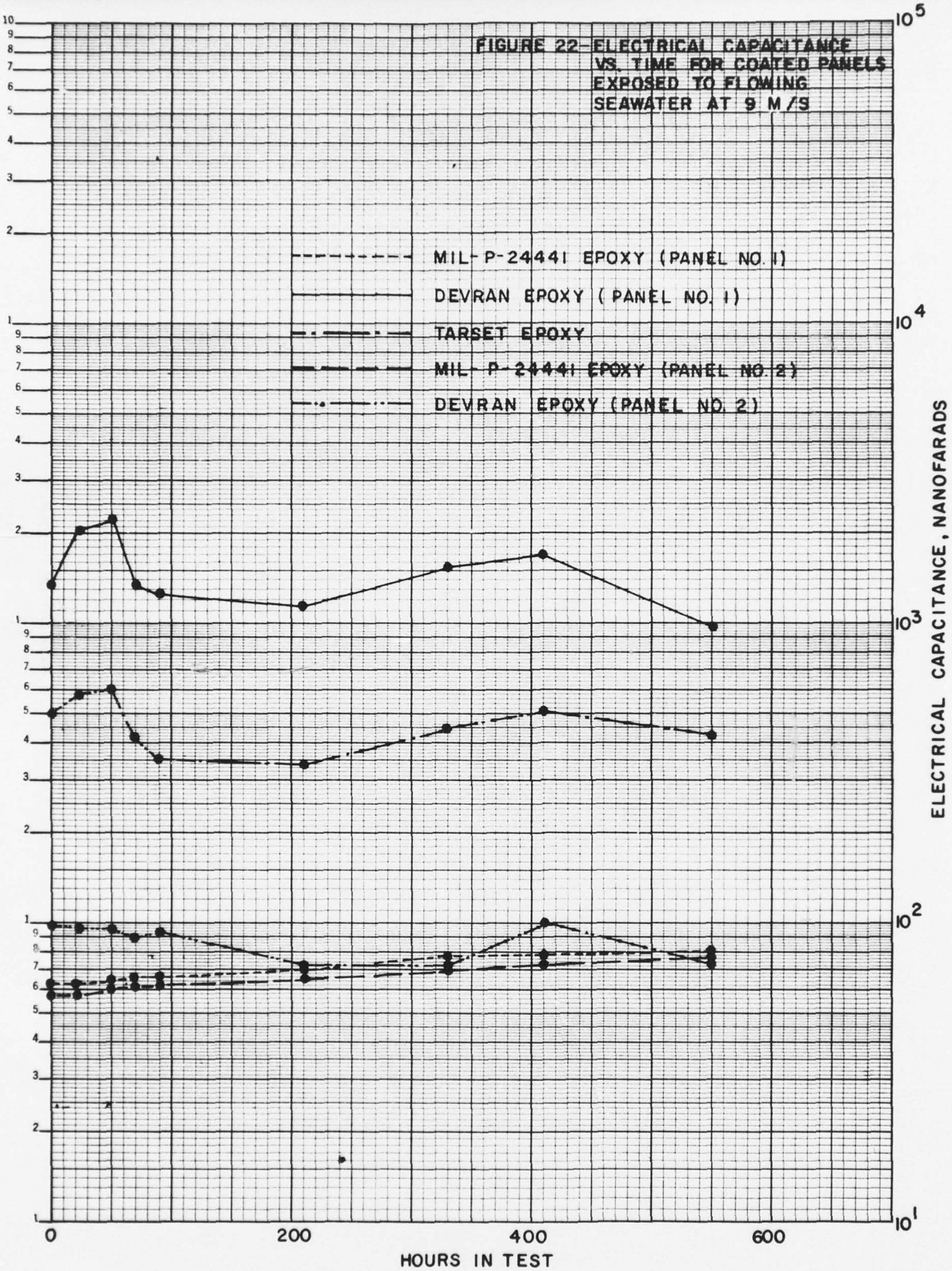


FIGURE 22- ELECTRICAL CAPACITANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 9 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
ELECTRICAL CAPACITANCE, NANOFARADS
HOURS IN TEST
0
200
400
600
10^5
10^4
10^3
10^2
10^1

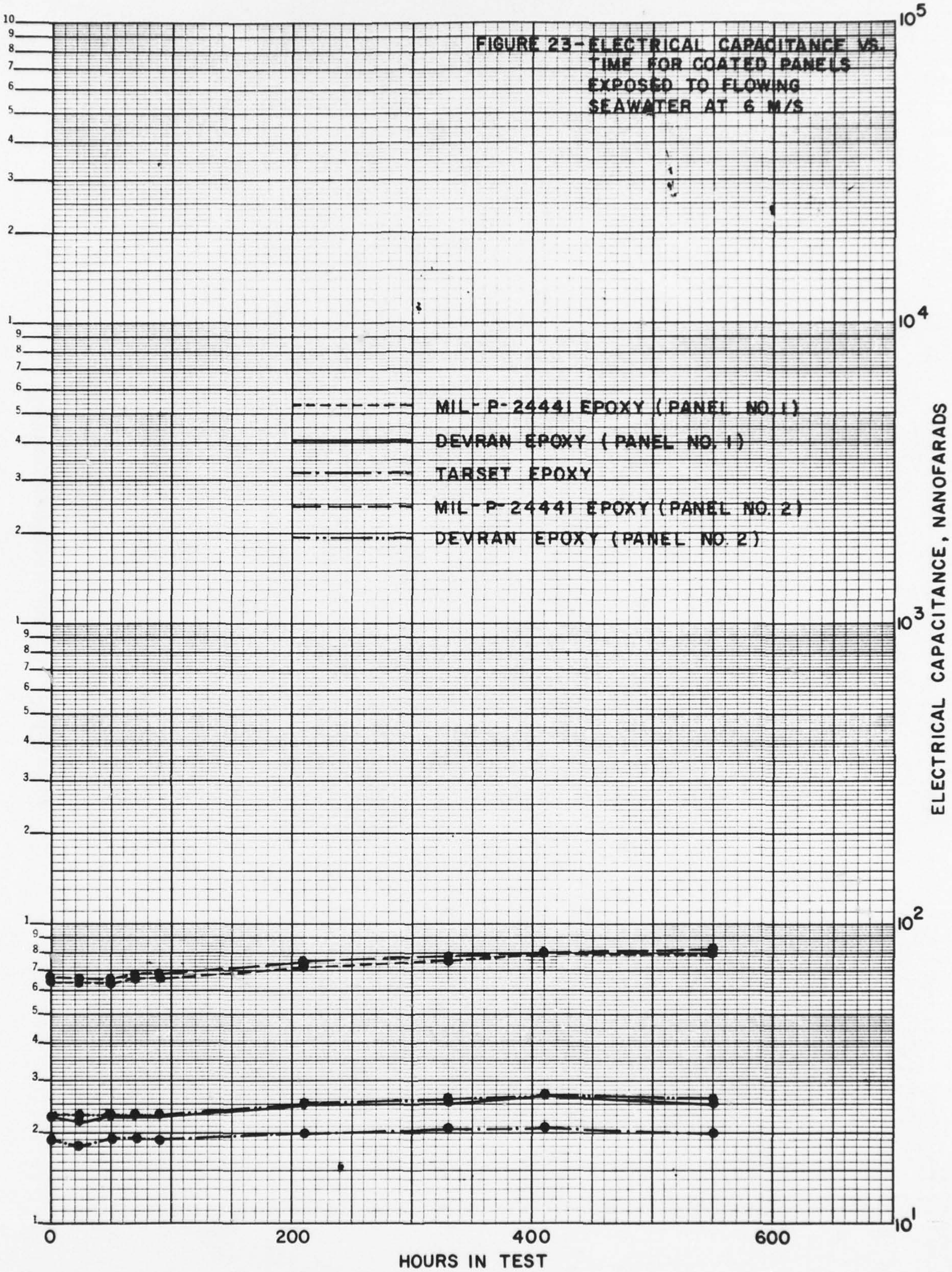


FIGURE 23-ELECTRICAL CAPACITANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 6 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
ELECTRICAL CAPACITANCE, NANOFARADS
HOURS IN TEST
0
200
400
600
10^5
10^4
10^3
10^2
10^1

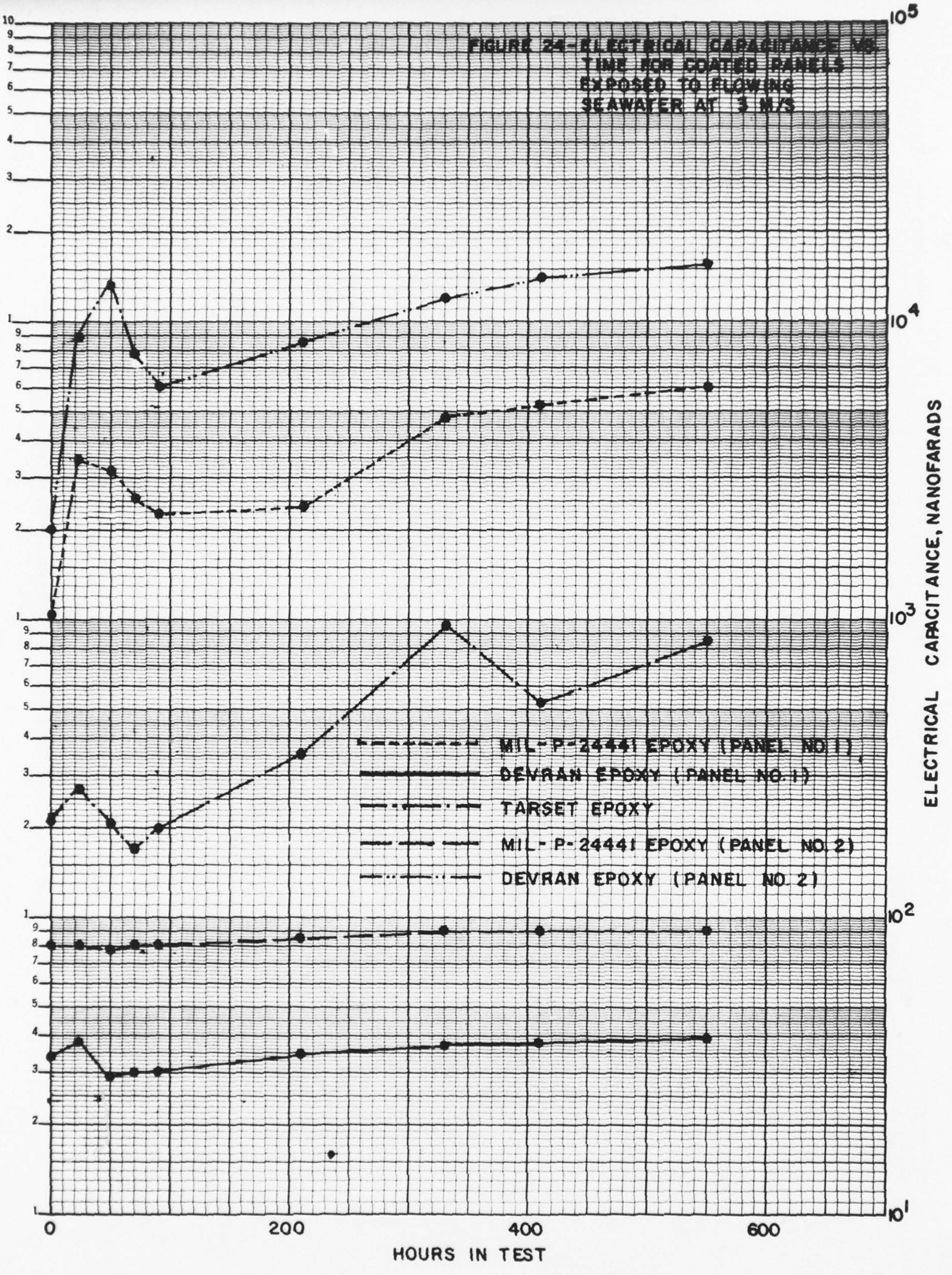


FIGURE 24-ELECTRICAL CAPACITANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 3 M/S
MIL-P-24441 EPOXY (PANEL NO.1)
DEVRAN EPOXY (PANEL NO.1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO.2)
DEVRAN EPOXY (PANEL NO.2)
HOURS IN TEST
ELECTRICAL CAPACITANCE, NANOFARADS
0
200
400
600
10^1
10^2
10^3
10^4
10^5

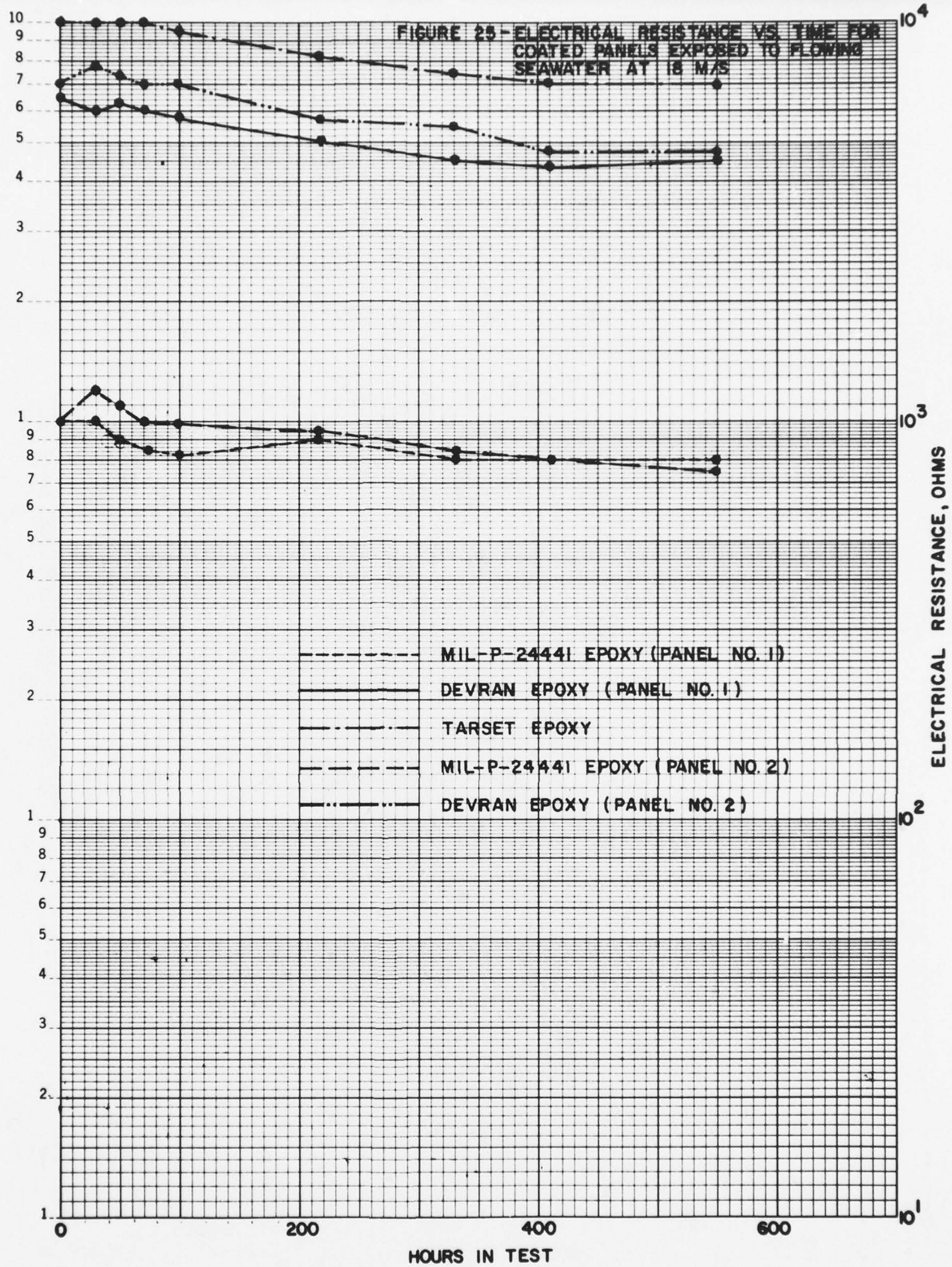


FIGURE 25 - ELECTRICAL RESISTANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 18 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
ELECTRICAL RESISTANCE, OHMS
HOURS IN TEST
0
200
400
600
10^4
10^3
10^2
10^1

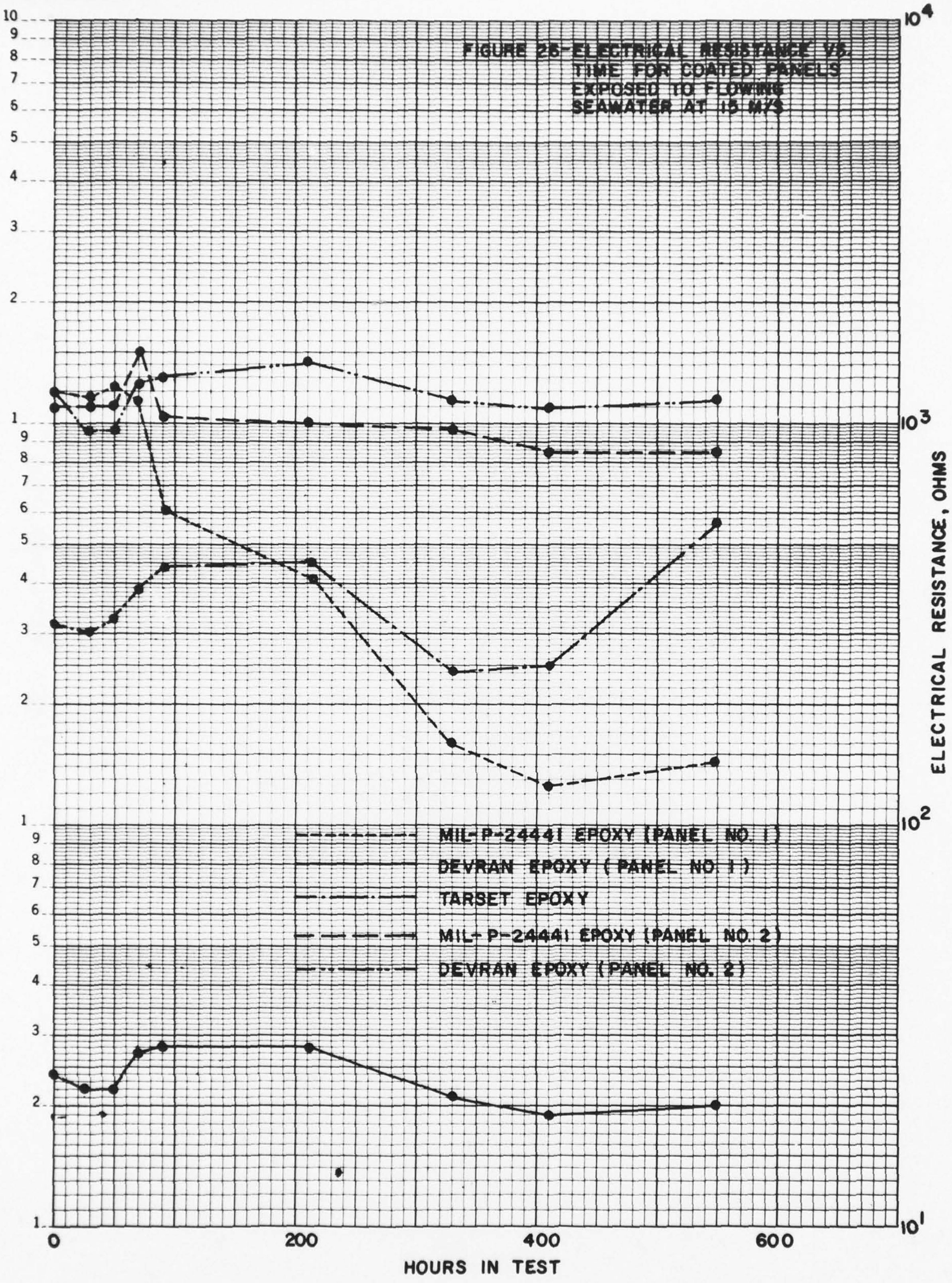


FIGURE 26-ELECTRICAL RESISTANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 15 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
ELECTRICAL RESISTANCE, OHMS
HOURS IN TEST
0
200
400
600
10^1
10^2
10^3
10^4

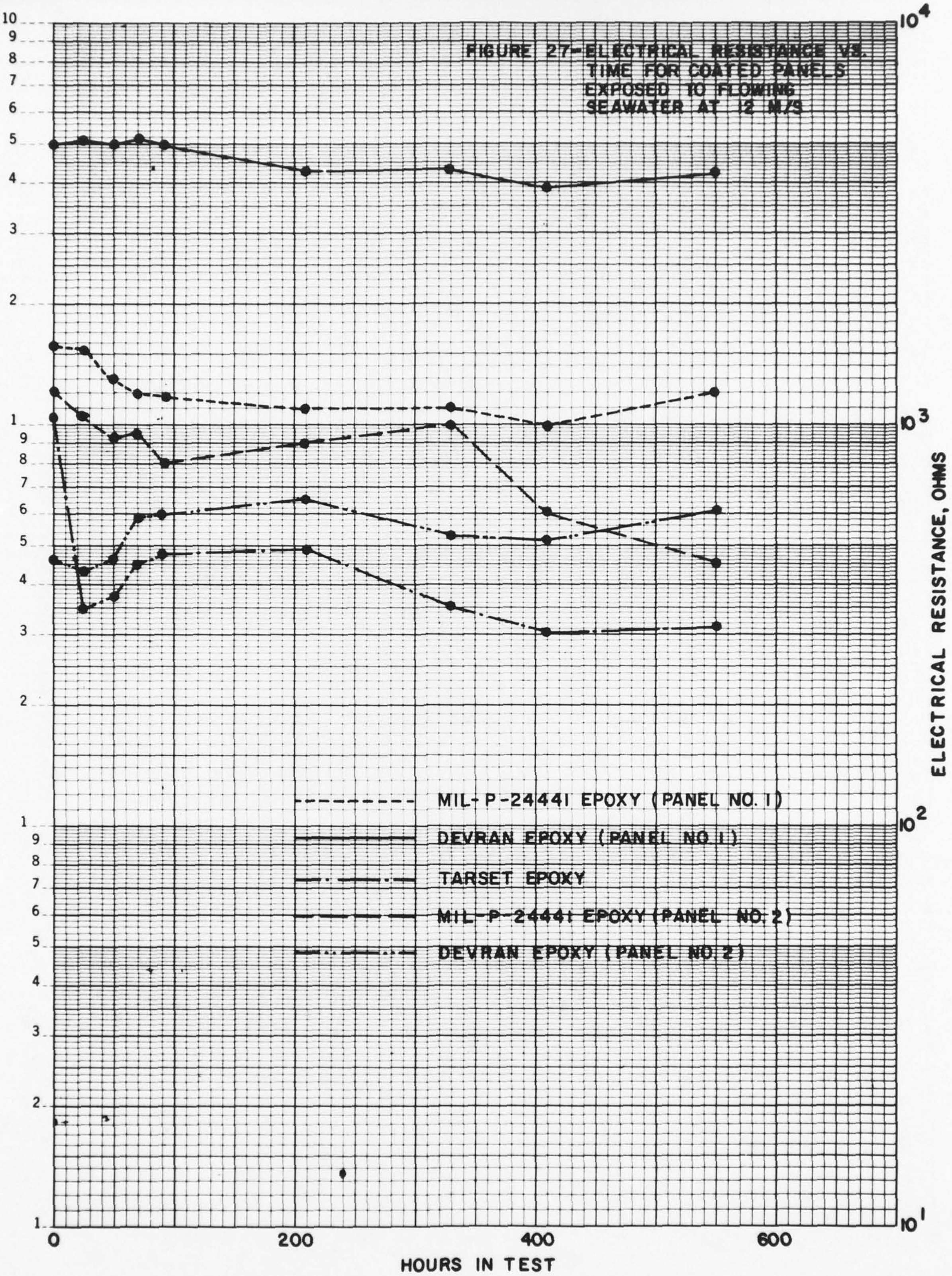


FIGURE 27-ELECTRICAL RESISTANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 12 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
10^4
10^3
10^2
10^1
ELECTRICAL RESISTANCE, OHMS
0
200
400
600
HOURS IN TEST

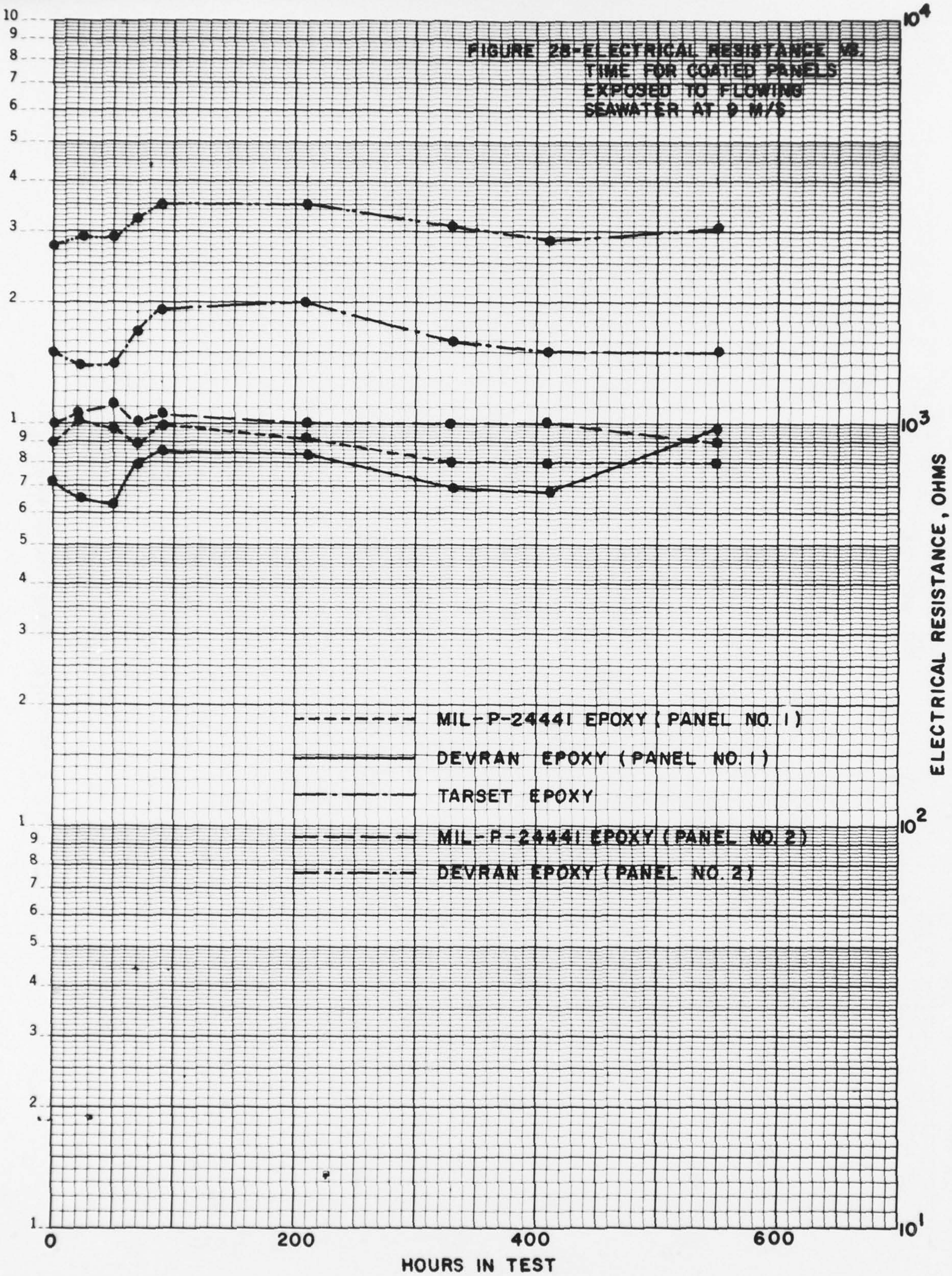


FIGURE 28-ELECTRICAL RESISTANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 9 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
ELECTRICAL RESISTANCE, OHMS
HOURS IN TEST
0
200
400
600
10^4
10^3
10^2
10^1

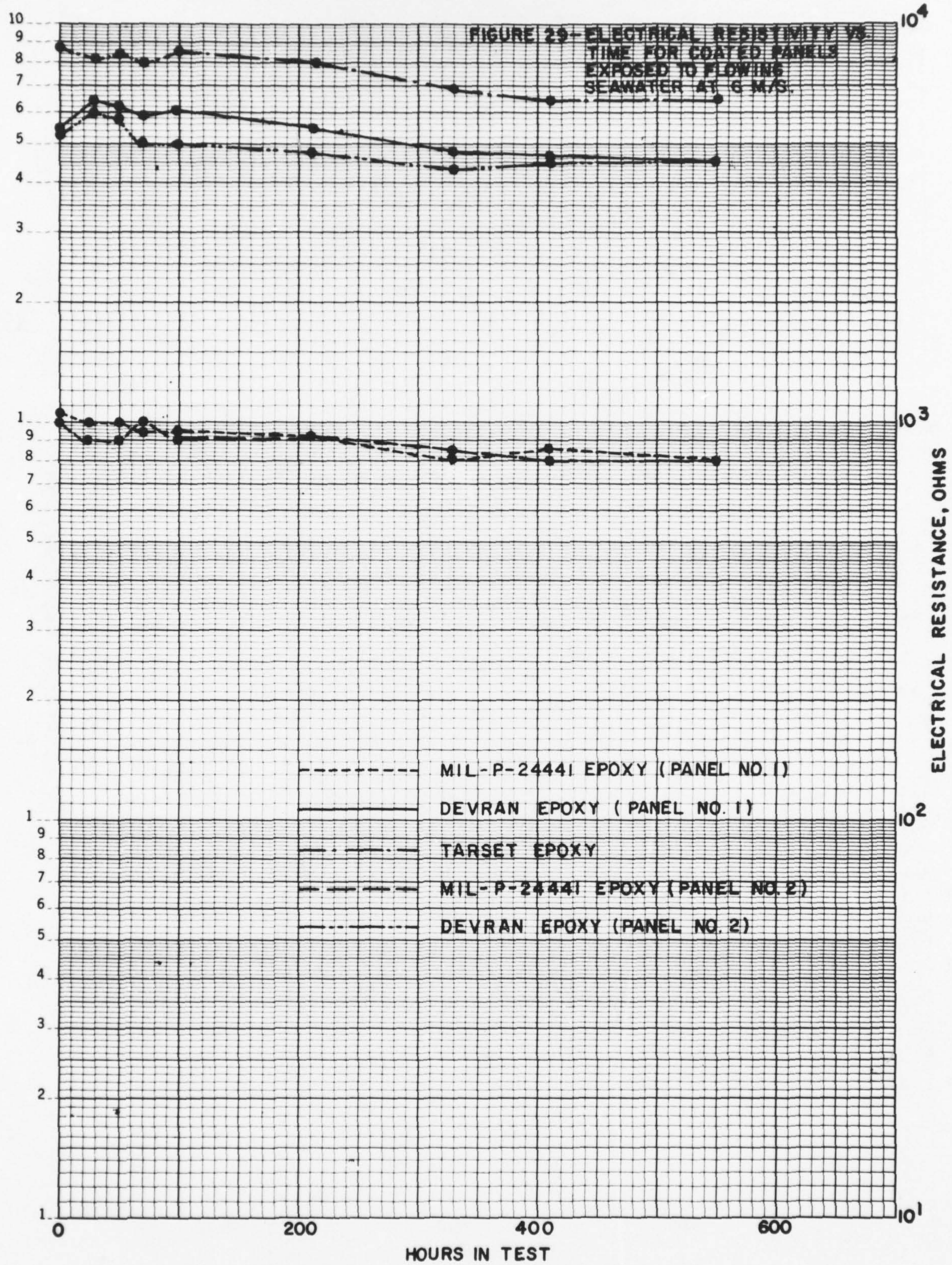


FIGURE 29- ELECTRICAL RESISTIVITY VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 6 M/S.
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
HOURS IN TEST
ELECTRICAL RESISTANCE, OHMS
0
200
400
600
10^4
10^3
10^2
10^1

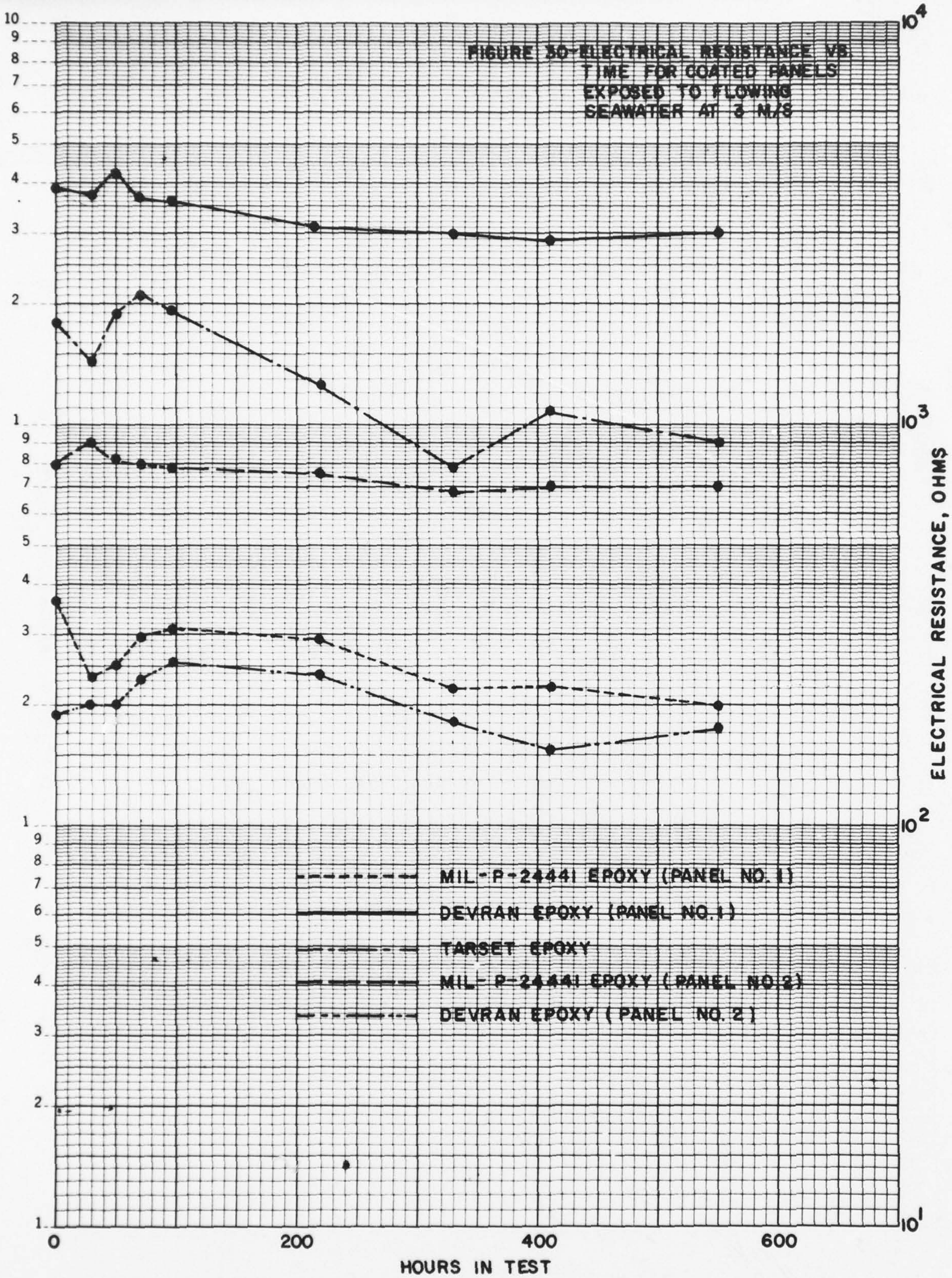


FIGURE 30-ELECTRICAL RESISTANCE VS. TIME FOR COATED PANELS EXPOSED TO FLOWING SEAWATER AT 3 M/S
MIL-P-24441 EPOXY (PANEL NO. 1)
DEVRAN EPOXY (PANEL NO. 1)
TARSET EPOXY
MIL-P-24441 EPOXY (PANEL NO. 2)
DEVRAN EPOXY (PANEL NO. 2)
ELECTRICAL RESISTANCE, OHMS
HOURS IN TEST
0
200
400
600
10^4
10^3
10^2
10^1

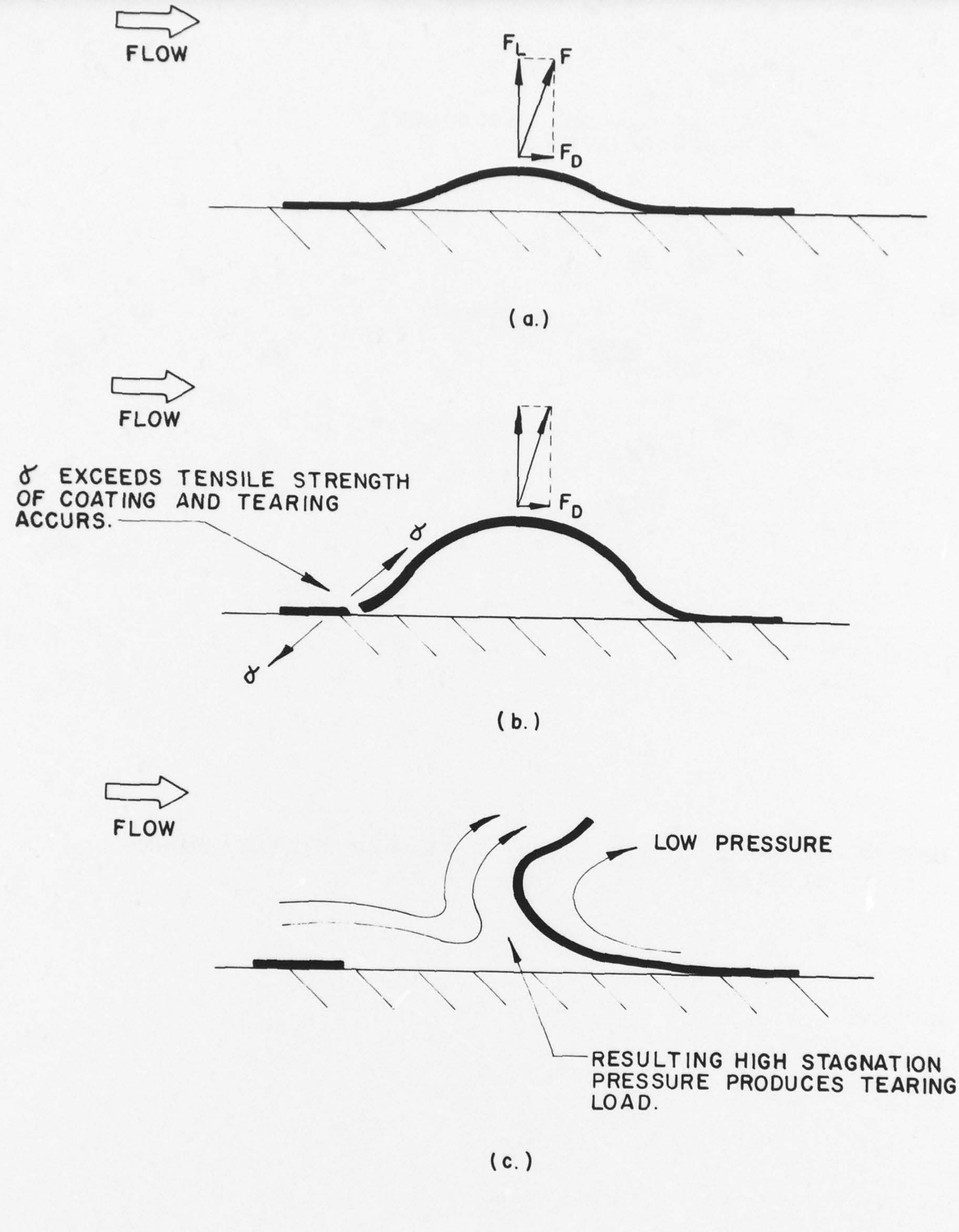


FIGURE 31 – POSSIBLE COATING FAILURE MECHANISM AT HIGH VELOCITY.

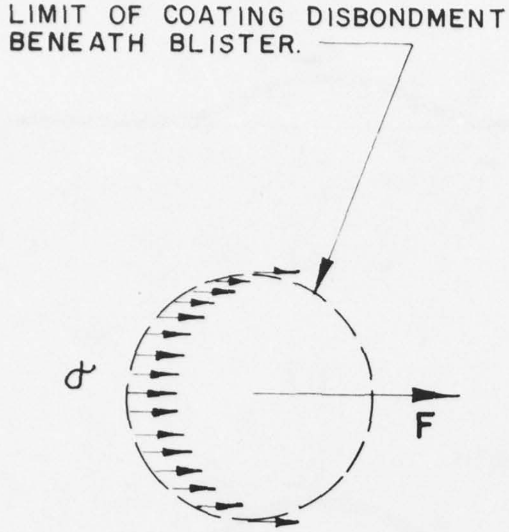


FIGURE 32 – POSSIBLE DISTRIBUTION OF TENSILE STRESS AROUND BLISTER.